NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

UNMANNED SYSTEMS IN INTEGRATING CROSS-DOMAIN NAVAL FIRES

by

Systems Engineering Analysis
Cohort 23

June 2016

Project Advisors: Fotis Papoulias
Michael Atkinson

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2016	**3. REPORT TYPE AND DATES COVERED** capstone project report	
4. TITLE AND SUBTITLE UNMANNED SYSTEMS IN INTEGRATING CROSS-DOMAIN NAVAL FIRES			**5. FUNDING NUMBERS**
6. AUTHOR(S) Systems Engineering Analysis, Systems Engineering Cohort 23			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The ability to communicate and transmit targeting data via the electromagnetic spectrum is crucial to the Navy's ability to fight. However, in recent years, potential adversaries have significantly advanced their electronic warfare capabilities, obtaining an ability to interfere with the Navy's use of the electromagnetic spectrum during operations in contested environments.

SEA23 investigates concepts of operation focusing on future potential electromagnetic-spectrum warfighting capabilities in the 2025–2030 timeframe. Specifically, we explore these capabilities using modular unmanned and manned platforms capable of carrying communications and data suites to enable cross-domain targeting information in support of tactical offensive operations in a contested, denied, degraded, intermittent, and limited-bandwidth environment. This project focuses on developing a system-of-systems architecture and analyzing alternatives to provide potential solutions while developing the associated concepts of operation. We recommend an architecture based on Link 16 and organic rotary-wing unmanned aerial vehicles to transfer sensor to shooter data in demanding and contested environments.

14. SUBJECT TERMS unmanned systems, cross domain, unmanned aerial vehicles, naval fires, targeting, distributed lethality, anti-access, area denial; denied, disrupted, degraded, low-bandwidth environment			**15. NUMBER OF PAGES** 197
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

UNMANNED SYSTEMS IN INTEGRATING CROSS-DOMAIN NAVAL FIRES

Systems Engineering Analysis, Systems Engineering Cohort 23

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING ANALYSIS

from the

NAVAL POSTGRADUATE SCHOOL
June 2016

LT J.R. Cox, USN
LT David Erstad, USN
LT John Fisher, USN
CPT David Hanna, USA
LT Zach Martens, USN
LT Tim Reeves, USN
CPT Brandon Wagner, USA

WITH

LT Sophia Bay, USN
CPT Roey Ben Yoash, IDF
CPT Chun Chieh Cheng, SA
MAJ Guoquan Lai, SA
Jin Wei Lai
Kum Leong Lee
CPT Eng Soon Lim, SA
CPT Wee Yeow Lim, SA
CPT Jianwen Lim, SA
LT Nelson Mitchell, USN
Chee Kiong Ong
CPT Weihao Kevin Soon, SA
MAJ Chew Kung Tan, SA
CPT Kenny Sheng Yong Teo, SA
CDR Kevin Williams, USN
CPT Chee Mun Kelvin Wong, SA
Kuhai Wong
Kam Wah Wu
Siew Peng Yue
CPT Zhibin Zhang, SA

Lead editor: David Erstad

Reviewed by:
Fotis Papoulias
Project Advisor

Michael Atkinson
Project Advisor

Accepted by:
Ronald Giachetti
Systems Engineering Department

Patricia Jacobs
Operations Research Department

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The ability to communicate and transmit targeting data via the electromagnetic spectrum is crucial to the Navy's ability to fight. However, in recent years, potential adversaries have significantly advanced their electronic warfare capabilities, obtaining an ability to interfere with the Navy's use of the electromagnetic spectrum during operations in contested environments.

SEA23 investigates concepts of operation focusing on future potential electromagnetic-spectrum warfighting capabilities in the 2025–2030 timeframe. Specifically, we explore these capabilities using modular unmanned and manned platforms capable of carrying communications and data suites to enable cross-domain targeting information in support of tactical offensive operations in a contested, denied, degraded, intermittent, and limited-bandwidth environment. This project focuses on developing a system-of-systems architecture and analyzing alternatives to provide potential solutions while developing the associated concepts of operation. We recommend an architecture based on Link 16 and organic rotary-wing unmanned aerial vehicles to transfer sensor to shooter data in demanding and contested environments.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	Anti-Access / Area Denial
ACTUV	Anti-submarine Continuous Trail Unmanned Vehicle
AD	Area Denial
ADL	advanced datalink
ADT	administrative delay time
AEGIS	AEGIS Combat System
AFP	adaptive force package
AGM	air-to-ground missile
AO	Area of Operation
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
ASM	air-to-surface missile
C2	command and control
C4I	Command, Control, Communications, Computers and Intelligence
CDMaST	Cross-Domain Maritime Surveillance and Targeting
CEC	Cooperative Engagement Capability
CISR	communications, intelligence, surveillance, and reconnaissance
CNAF	Commander, Naval Air Forces
CNO	Chief of Naval Operations
CNSF	Commander, Naval Surface Forces
COA	courses of action
COI	Critical Operational Area
COIC	Critical Operational Area Criteria

COMPACFLT	Commander, Pacific Fleet
CONOPS	concept of operations
CONUS	Continental United States
COTF	Commander, Operational Test and Evaluation Force
COTS	commercial off-the-shelf
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CSBA	Center for Strategic and Budgetary Assessments
CSG	carrier strike group
CVN	nuclear aircraft carrier
CVW	carrier air wing
DARPA	Defense Advanced Research Projects Agency
DAW	distributed air wing
DAWO	distributed air wing operations
dBi	decibels-isotropic
DCA	defensive counter-air
DDG	guided missile destroyer
DDIL	denied, degraded, intermittent, and limited
DDL	digital datalink
DIME	diplomatic, informational, military, and economic
DL	distributed lethality
DOD	Department of Defense (U.S. Government)
DODAF	Department of Defense Architecture Framework
DON	Department of the Navy

DOE	design of experiments
DR	data requirement
DTE	detect-to-engage
EEZ	exclusive economic zone
EM	electromagnetic
EMW	electromagnetic warfare
EMALS	Electromagnetic Aircraft Launch System
EMCON	emission control
ESG	expeditionary strike group
ESOH	environmental, safety, occupational health
EW	electronic warfare
FFBD	functional flow block diagram
FFC	Fleet Forces Command
FFG	guided missile frigate
FLIR	forward-looking infrared
GAMS	general algebraic modeling system
GPS	Global Positioning System
GOTS	government off-the-shelf
HVU	high-value unit
IAMD	integrated air and missile defense
ICOM	inputs, controls, outputs and mechanisms
IDEF0	Integrated Computer Aided Manufacturing (ICAM) Definition for Functional Modeling
INCOSE	International Council on Systems Engineering

INS	inertial navigation system
IOC	initial operational capability
IPR	interim progress review
IRB	Institutional Review Board
ISR	intelligence, surveillance, and reconnaissance
JASSM	joint air-to-surface standoff missile
JCIDS	Joint Capabilities Integration and Development System
JHUAPL	Johns Hopkins University Applied Physics Lab
Kpbs	Kilobytes per second
KPP	key performance parameter
LAMPS	Light, Airborne, Multi-purpose System
LCS	littoral combat ship
LDT	logistics delay time
LHA	amphibious assault ship (multi-purpose)
LOC	lines of communication
LOS	line-of-sight
LRASM	long-range anti-ship missile
MADL	multifunction advanced digital datalink
Mbps	Megabytes per second
MDT	maintenance down time
ME	mechanical engineering
MIDS/JTRS	Multi-functional Information Distribution System / Joint Tactical Radio System
MILCON	military construction

MILP	mixed integer linear program
MODAF	Ministry of Defence Architecture Framework
MOE	measure of effectiveness
MOP	measure of performance
MOS	measure of suitability
MOVES	Modeling Virtual Environments and Simulation
MSC	Military Sealift Command
MT	maintenance time
NATOPS	Naval Air Training and Operating Procedures Standardization
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NAWDC	Naval Air Warfare Development Center
NDP	Naval Doctrine Publication
NM	nautical mile
NPS	Naval Postgraduate School
NSMWC	Naval Surface and Mine Warfighting Development Center
NUS	National University of Singapore
NWDC	Navy Warfare Development Command
OCA	offensive counter-air
OPNAV	Office of the Chief of Naval Operations
OPNAV N9I	Office of the Chief of Naval Operations Warfare Integration Division
OR	operations research
OTH	over-the-horizon

OV	operational view
PACFLT	Pacific Fleet
PEO/IWS	Program Executive Office / Integrated Warfare System
PLA	People’s Liberation Army
PLA (N)	People’s Liberation Army (Navy)
PNT	positioning, navigation, and timing
PRC	People’s Republic of China
R&D	research and development
RAND	random
RCS	radar cross section
RF	radio frequency
RFP	request for proposal
SADL	situational awareness datalink
SAG	surface action group
SAM	surface-to-air missile
SATCOM	satellite communications
SCS	South China Sea
SE	systems engineering
SEA	systems engineering analysis
SEA23	Systems Engineering Analysis Cohort 23
SEA21A	Systems Engineering Analysis Cohort 21-Alpha
SEAD	suppression of enemy air defenses
SIGNIT	signals intelligence
SOCOM	Special Operations Command

SOFA	status of forces agreement
SOS	system of systems
SPAWAR	Space and Naval Warfare Systems Command
SRBM	short-range ballistic missile
SSG	Strategic Studies Group
SSK	diesel powered submarine
SSN	nuclear powered attack submarine
STOVL	short take-off and vertical landing
SUBDEVRON	Naval Submarine Development Squadron
TACSIT	tactical situation
TAO	tactical action officer
TBD	to be determined
TDL	tactical datalink
TDSI	Temasek Defence Systems Institute
TEMP	test and evaluation master plan
TERN	Tactically Exploited Reconnaissance Vehicle
TLAM	Tomahawk land-attack missile
TRL	technology readiness level
TTPs	tactics, techniques, and procedures
UAS	unmanned aerial system
UAV	unmanned air vehicle
UCAS	unmanned combat aerial system
UCLASS	unmanned carrier airborne surveillance and strike
UCAV	unmanned combat air vehicle

UN	United Nations
UNCLASS	unclassified
UNCLOS	United Nations Convention on the Law of the Sea
UNTL	Universal Naval Task List
USMC	United States Marine Corps
USN	United States Navy
USV	unmanned surface vehicle
UUV	unmanned underwater vehicle
UxV	unmanned vehicle
VLS	vertical launching system
VTOL	vertical takeoff and landing
WTI	weapons tactics instructor

EXECUTIVE SUMMARY

The proliferation of land and sea-based platforms capable of projecting a highly sophisticated, effective and integrated anti-access, area-denial environment poses a significant problem for the U.S. Navy. In these environments, the current fleet methods for tactical offensive operations from the sea are frequently deemed high-risk (i.e., carrier strike groups) or incapable of projecting sufficient power (i.e., a small surface action group). The need for resilient strike capabilities in a high-risk combat environment, results in capability gaps that exist with current systems. The Systems Engineering Analysis Cohort 23 (SEA23) was tasked with developing a system of systems (SOS) to integrate cross-domain naval fires in these combat situations, with potential for fielding in the 2025–2030 period.

Tasking from the project sponsor, OPNAV N9I (Deputy Director for Warfare Integration), was broad in scope. However, after conducting a stakeholder analysis, SEA23 decided to narrow the focus to the communication of fire control data between a forward sensing platform to a firing platform because of current capability gaps. The project team explored and analyzed multiple manned and unmanned systems and tactical data link networks that could be suitable in the requested time period, and pared down the original tasking statement as follows:

> SEA23 will investigate a concept of operations in a contested environment using modular unmanned and manned platforms capable of carrying communications and data suites to enable cross-domain targeting information in support of tactical offensive operations in a contested, denied, degraded, intermittent, and limited bandwidth environment (DDIL).

SEA23 made critical assumptions to scope the project and enable completion in a nine-month period. The first major assumption is that the degradation of GPS will be graceful. In addition, alternate methods of precision navigation and determining time exist for weapons targeting. The second major assumption is the surface action group employed for assessing system alternatives consists of three Arleigh Burke class guided missile destroyers, allowing exploration into the concept of distributed lethality (Rowden

et al. 2015). Finally, we assume the system needs to rely on line-of-sight relay to overcome DDIL challenges. This situation is a good application for mesh networking due to their dynamic and ad hoc nature. In a changing environment, “the ability of self-organization, self-discovering, self-healing, and self-configuration” (Misra et al. 2009) inherent in mesh networks is highly prized. These assumptions enabled the research efforts to focus on the network architecture, type and requisite supporting platforms.

Unmanned aerial vehicles (UAVs) were determined to be the best systems to structure a tactical targeting relay network in the DDIL environment to achieve long-range line-of-sight capabilities. Near fully autonomous UAVs carry the proposed network hardware, which can operate collectively to support a mesh network. Figure 1 displays how the “Fire Web” communications network fits into a larger system providing offensive capability to Navy surface forces. A surface action group connects to remote sensing assets, either manned or unmanned, using the “Fire Web.” The sensing assets pass targeting quality data to the SAG that can engage the detected targets.

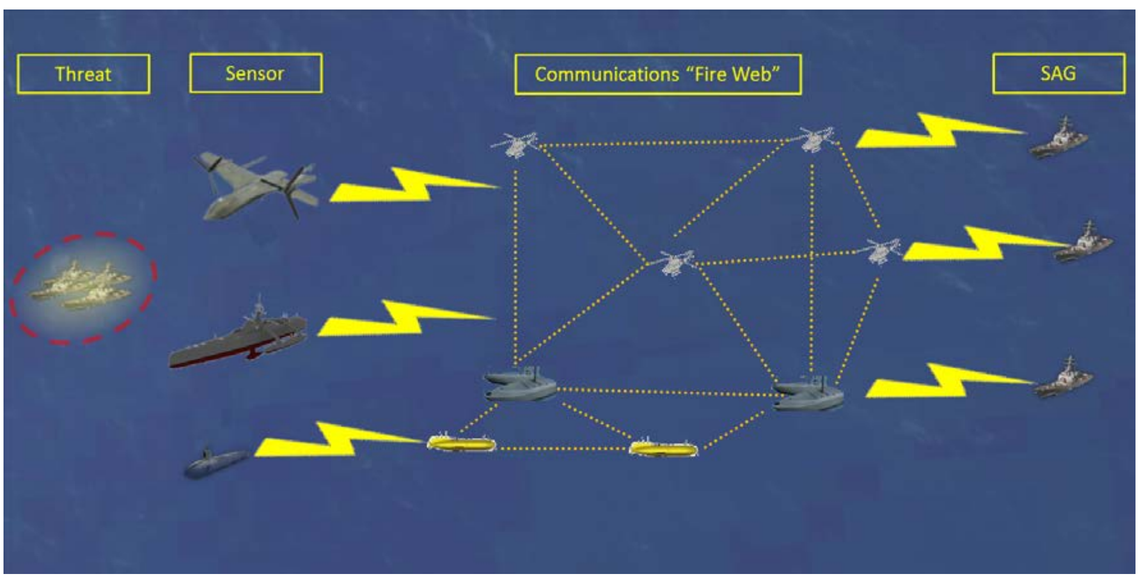


Figure 1. OV-1 Operational View.

Bounding the mesh network to line-of-sight communications establishes the system requirements for UAV separation, operational altitude, power requirements for transmission, payload capacity, and needed reliability, availability, and maintainability.

The extent of the network and subsequent required quantity of UAVs is dependent on the weapon range and uncertainty of the enemy's location, which shape the total area required for the network to cover. SEA23 based weapon range on the open source data for the long-range anti-ship missile (LRASM), which is 500 nautical miles, and an uncertainty arch of 180 degrees. Using a semi-circle with 500 nautical mile radius along the threat axis provides the required coverage area for the UAV based mesh communication relay network. This creates a worst-case scenario for the SAG's UAV carrying capacity and allows growth for the future of the system.

The alternatives for transferring data used current U.S. Navy tactical data links, and potential tactical links that suited the network architecture and concept well. SEA23 examined and analyzed Link-16, Cooperative Engagement Capability (CEC), and other UAV based data links to determine their suitability within the stakeholder and derived requirements, with an eye on future weapons system development. The team verified the networks for acceptable transmission range using basic electromagnetic physics, which provided valuable insight to the quantity of UAVs required given the area to cover (Table 1).

Table 1. Tradeoffs for Selected Tactical Data Links.

Tradeoffs for Selected TDLs			
	Link-16	**Cooperative Engagement Capability (CEC)**	**Other**
Physical Size	**7.62 x 7.5 x 13.5 inches**	**24 x 24 x 36 inches**	**9 x 6 x 2 inches**
Weight	**50 lbs**	**500 lbs**	**0.2 – 2 lbs**
Power assumed	**200 W**	**200 W**	**200 W**
Band	**L Band**	**C Band**	**Various**
	950-1250 MHz	**4-8 GHz**	**2-9 MHz**
Data Rate	**26.8 - 1102 kbps**	**5 Mbps**	**4.5 – 9 Mbps**
Range	**325 NM**	**119 NM**	**50 NM**

SEA23 selected UAV alternatives considering their launch and recovery requirements, storage area aboard surface combatants, and the range and payload requirements of the network hardware. As a function of the launch and recover process, a rotary type UAV was determined to be best suited to the system. The hangar area aboard the ships for the UAVs was constrained by the cubic size of a collapsed MH-60 Seahawk helicopter. The payload, range, launch, and recovery requirements narrowed the search for UAVs to three existing platforms: MQ-8B Fire Scout, DP-5X Wasp, and DP-14 Hawk. The three UAVs provide known rotary wing capabilities suitable for this analysis.

The analysis results of the potential tactical data link networks and UAV platforms, constrained by physical environment, payload weight, ranges, and transportation yielded three conclusions

1. The Link-16 data link is the only viable alternative of those data links studied due to its long range and lighter weight.

2. The preferred solution, using a Link-16 data link and DP-5X Wasp UAVs, and retaining the three-ship SAG may require sacrificing MH-60 helicopters to ensure sufficient UAV hanger space. Due to limitations with data rates, using Link 16 constrains the SAG's anti-air warfare (AAW) capability that also relies on this link for data transfer. The loss of MH-60s decreases the ship's ability to conduct search and rescue, anti-submarine warfare, and personnel transportation, including medical evacuations.

3. Adding a littoral combat ship (LCS) to the SAG is an additional alternative to increase UAV capacity or retain manned helicopter capability.

A rotary UAV capable of supporting a Link-16 data link system is considered feasible to develop, and will provide a seamless integration with sea-based integrated fire control. The DP-5X rotary UAV supports the payload requirement for the Link-16 data link system today, and will most readily support the SOS architecture that is proposed (Figure 2).


Figure 2. DP-5X Wasp in Flight.

References

Dragonfly Pictures, Inc. 2014. “DP-5X Wasp.” Accessed April 24. http://www.dragonflypictures.com/products/unmanned-vehicles/dp-5x-wasp/

Rowden, Thomas and Peter Gumataotao and Peter Fanta. 2015. “Distributed Lethality.” *Proceedings*. http://www.usni.org/magazines/proceedings/2015-01/distributed-lethality.

Misra, Sudip and Subhas Chandra Misra and Isaac Woungang, editors. 2009. *Guide to Wireless Mesh Networks*. Swindon: Springer-Verlag London Limited.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

Systems Engineering Analysis Cohort 23 (SEA23) thanks our faculty advisor, Department of Systems Engineering Associate Professor Dr. Fotis Papoulias, for his assistance and guidance through the capstone study process. Additionally, SEA23 thanks the faculty of the Systems Engineering and Operations Research Departments for their instruction, which gave us the ability to complete this study. The study's completion depended on their dedication to providing us with the necessary intellectual tools.

While many individuals on the NPS campus and throughout the Department of Defense provided information and guidance, there were persons whom SEA23 would like to specifically identify for their support:

CAPT (Ret.) Wayne Hughes, NPS

CAPT (Ret.) Jeffrey Kline, NPS

CAPT Chuck Good, USN

CDR (Ret.) Matthew Boensel, NPS

LTC (Ret.) Mark Stevens, NPS

Dr. Michael Atkinson, NPS

SEA23 would also like to thank our families for their support and dedication throughout our time spent at NPS and specifically during this capstone project.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

The United States Navy (USN) is currently researching the ability to conduct operations in an Anti-Access, Area Denial (A2AD) environment where potential enemies can hold surface ships at risk. Systems Engineering Analysis Cohort 23 project team had tasking to design a system of systems (SOS) network incorporating the integration of cross-domain targeting information in a 2025–2030 time frame employed in a contested area where use of the electromagnetic spectrum is constrained by potential adversary actions. SEA23 used the South China Sea as a foundational scenario to assess network alternatives, based on the increasing tensions and widespread operational complications of the A2AD environment.

Distributed lethality (DL) is a developing concept within the surface warfare community. It defines the ability for small groups of surface forces to provide overwhelming amounts of offensive firepower against an adversary. Furthermore, it involves a purely distributed and integrated force capable of providing organic levels of command and control (C2), offensive firepower, and power projection (Rowden et al. 2015). Distributed lethality provides a framework and focus in development of a Concept of Operations (CONOPS) to support offensive surface warfare forces. A major component of this project uses a surface action group (SAG) of three destroyers, with an understanding of capabilities and limitations, to seek a network, integrated solution to provide reliable targeting information in a contested environment.

A. PROJECT TEAM

Systems Engineering Analysis Cohort 23 (SEA23) is comprised of students from the Naval Postgraduate School (NPS) and the National University of Singapore's Temasek Defence Systems Institute (TDSI), with each student bringing a unique set of experiences and knowledge to bear on the project's tasking. Four surface warfare officers, two naval aviators, a submariner, a human resources officer, and two Army acquisitions officers represent the U.S. members of the team. Additionally, the team's TDSI students include an Israeli infantry officer as well as members of Singapore's

Army, Navy, and civilian defense industry (Table 1). Altogether, SEA23 has considerable real world experience to bring to bear upon the project tasking. SEA23's TDSI student members study many academic subject areas in addition to their operational experiences. The team members are studying operations research and analysis, computer science, mechanical and electrical engineering, oceanography, and physics.

Table 1. SEA23 Project Team Composition.

SEA23 Capstone Project Advisor Dr. Fotis Papoulias (NPS Associate Professor, Systems Engineering)
SEA23 Subject-Matter Experts CAPT (Ret.) Jeffrey Kline (NPS Professor of Practice, Operations Research) CAPT Chuck Good (COMNAVSURFPAC detachment Monterey) CDR (Ret.) Matthew Boensel (NPS Associate Professor, Systems Engineering)
SEA23 Capstone SEA Students LT J.R. Cox (Surface Warfare Officer) LT David Erstad (Surface Warfare Officer) LT John Fisher (Aviation, F/A-18C/D Hornet Pilot) Cpt. David Hanna (Army Acquisitions) LT Zach Martens (Surface Warfare Officer) LT Tim Reeves (Surface Warfare Officer) Cpt. Brandon Wagner (Army Acquisitions) SEA23 TDSI Students LT Sophia Bay (Human Resources Officer) Cpt. Roey Ben Yoash (Israeli Army, Infantry) Cpt. Chun Chieh Cheng (Singapore Army, CBRE/CBRN) MAJ Guoquan Lai (Singapore Army, Signals) Jin Wei Lai Kum Leong Lee Eng Soon Lim (Singapore Army, Armor) Wee Yeow Lim (Singapore Army, Artillery) Jianwen Lin (Singapore Army, Signals) LT Nelson Mitchell (Submariner) Chee Kiong Ong

(continued on next page)

Table 1 (continued)

Weihao Kevin Soon (Singapore Army, Vehicle, Maintenance)
MAJ Chew Kung Tan (Singapore Navy, Electronic Warfare)
Cpt. Kenny Sheng Yong Teo (Singapore Army, Artillery)
CDR Kevin Williams (Aviation, P-3 Naval Flight Officer)
Cpt. Chee Mun Kelvin Wong (Singapore Army, Air Defense Acquisitions)
Luhai Wong
Kam Wah Wu
Siew Peng Yue
Zhibin Zhang (Singapore Army, Artillery/IT)

B. PROJECT BACKGROUND

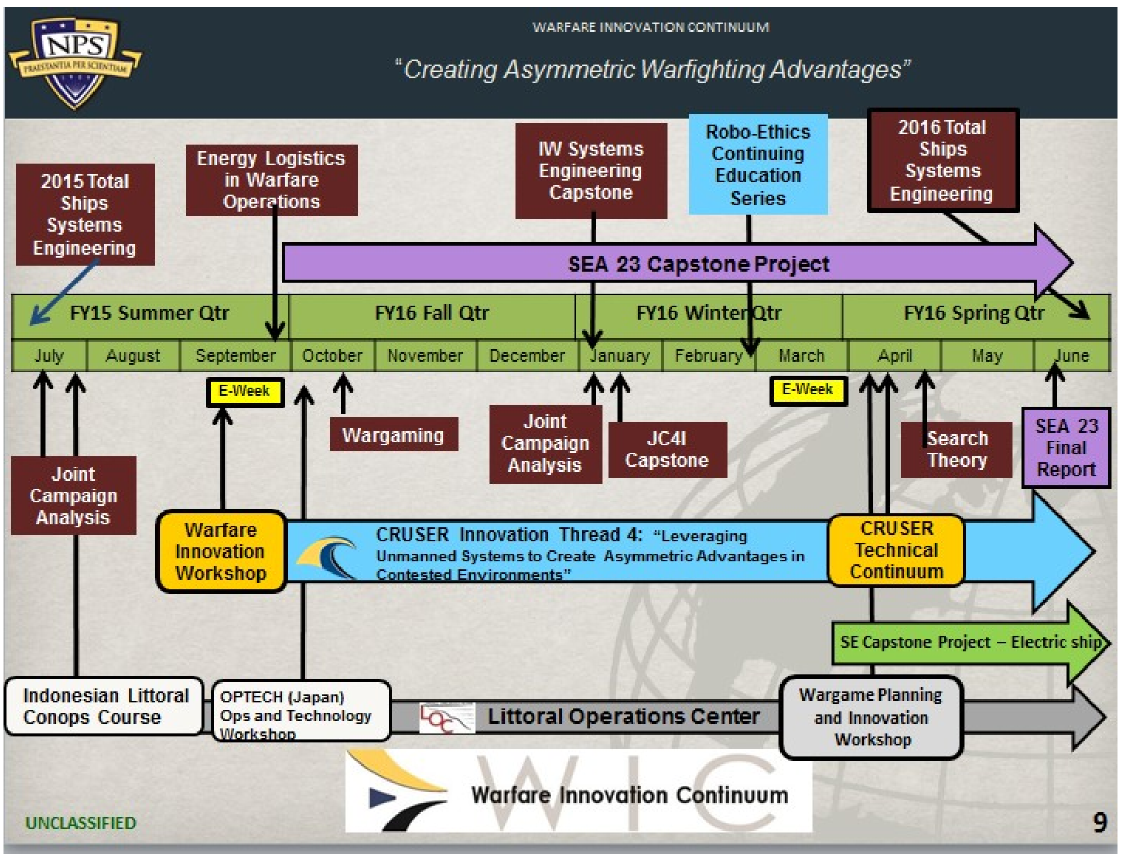
The SEA curriculum combines a variety of systems engineering, combat systems, and operational analysis courses culminating in the application of a systems analysis approach to the project. As defined by NPS,

> Systems Analysis provides key insights for improved operation of existing complex defense systems; it examines existing systems to better understand them. This understanding is then used to determine and choose among alternatives for system design, improvement and employment. Systems analysts apply modeling, optimization, simulation, and decision making under risk and uncertainty. (NPS 2015)

Ultimately, this program provides the USN and DOD with military professionals who are able to apply SE, operational analysis, and systems analysis to a wide range of complex problems. The curriculum structured provides a sound academic foundation in systems engineering and analysis for the first half of the two-year program. The second half continues to develop these academic skills by focusing on the practical application of completing a detailed and integrated capstone project.

SEA23 students first began considering their project during the Warfare Innovation Workshop during Enrichment Week, September 2015. This four-day forum brought together students and faculty, defense industry, and DOD employees at NPS. This unique innovative environment allows the free exchange of ideas and provides both the operational and research and development worlds to better understand each other's capabilities. The September 2015 theme was "Creating Asymmetric Warfighting

Advantages: Electromagnetic Maneuver Warfare," which was a jump-start to SEA23's project. The workshop had a stated mission of "advancing the [Chief of Naval Operations]'s concept of Electromagnetic Maneuver Warfare (EMW) and leveraging unmanned systems to enhance cross domain operations" (CRUSER 2015). It exposed SEA23 team members to various challenging operating environments for naval forces and alternative technologies to assist meeting those challenges. The SEA project and the Warfare Innovation Workshop were sub-sets of the larger Naval Postgraduate School Warfare Innovation Continuum titled "Creating Asymmetric Warfighting Advantages" (Figure 1).



SEA23 Final Production Review (FPR) briefing slide

Figure 1. NPS Warfare Innovation Continuum.

The Consortium for Robotics, Unmanned Systems, Education and Research (CRUSER) is comprised of students, academics, and government and industry professionals with a focus on unmanned and robotic systems as directed by the Secretary of the Navy (SECNAV). CRUSER focuses specifically on four goals (CRUSER 2015):

1. provide a source for unmanned systems employment concepts for operations and technical research
2. provide an experimentation program to evaluate unmanned system employment concepts
3. provide a venue for Navy-wide education in unmanned systems
4. provide a DOD-wide forum for collaborative education, research, and experimentation in unmanned systems

CRUSER sponsors and hosts the Warfare Innovation Workshop. For three to four days, it combines elements of design, divergent, and convergent thinking practices for innovative solutions. CRUSER Warfare Innovation Workshop’s structure has three segments.

1. New technology briefs
2. Small group problem solving development
3. Final brief presentations

The first portion of the working group provides students with an overview into various innovative technologies from both within and outside the government. The second portion divides the participants into numerous small groups that are a mix of personnel from government and industry. Small group tasking was to provide recommendations on developing technological solutions to an overall problem that DOD may encounter in the future. The final portion requires a formal brief from each group detailing their various conclusions developed during the individual team sessions. The numerous solutions and feedback generated during these formal presentations represent a wide range of ideas and possible topics for future research. Results proposed during the workshop ranged from simple mechanical systems to the use of quantum entanglement. This workshop provided SEA23 with a basic understanding of new technologies, networking opportunities with future stakeholders and interested parties, and the ability to

begin thinking abstractly about the capstone project. The workshop proved to be extremely helpful in examining possible avenues of research and solutions for our project.

The SEA23 capstone project officially began during the fall 2016 academic quarter (September–December 2015). Official project tasking and research exploration topics came through various DOD sources. OPNAV N9I Warfare Integration Division delivered SEA23's problem statement. SEA23 had three academic quarters to conceptualize, design, and implement a solution. The final deliverable is a written report and three phases of formal presentation. SEA23 delivers the presentations to NPS students and faculty, stakeholders, and other interested parties. The project problem statement required the group to design a SOS network fully incorporating the joint integration of cross-domain targeting information in a 2025–2030 contested area.

C. LITERATURE REVIEW AND TASKING EVOLUTION

The tasking statement required expertise in systems engineering, systems analysis, network optimization, and naval operations. SEA23 organized into subject matter teams to conduct research on the project's different themes. The topics that were covered included systems engineering methods, communications networks, and current unmanned vehicle technology. SEA23's project builds on the work completed by the previous cohort, SEA21A whose project involved surface-to-surface engagements and maritime intelligence, surveillance, and reconnaissance. SEA21A defined their project tasking as:

> Design a maritime intelligence, surveillance, reconnaissance (ISR), and targeting system of systems (SOS) and concept of operations capable of detecting, classifying, and engaging targets in support of [over-the-horizon] tactical offensive operations in a contested littoral area in the 2025–2030 timeframe. (SEA21A 2014)

Their project focused on the ability of organic Navy assets to launch UAVs to conduct targeting in an A2AD environment, reaching the conclusion that:

> The U.S. Navy shall develop an integrated network-centric surface-based UAV system capable of airspeeds in excess of 110 [knots] and sensor

ranges of greater than 130 NM to enhance surface fleet organic OTH first-strike capabilities within A2/AD environments by 2025. (SEA21A 2014)

SEA23 built on this thesis with a concentration on network relays in the denied, degraded, intermittent, and limited bandwidth (DDIL) environment. SEA23 conducted the research and analysis regarding the capability of the network to pass targeting data from the point of collection to the Command and Control (C2) node.

Mesh networks were not a familiar subject area and required the assistance of subject matter experts to introduce them. Naval Postgraduate School Professor and Chair of Information Sciences Department Dr. Dan Boger recently published "Agile EMCON" which focuses on frequency use affecting the C2 environment. Dr. Boger's paper and CRUSER presentation, as well as SEA23's personal interactions with him, provided a better understanding of how to leverage the electro-magnetic spectrum in a DDIL, A2AD environment for effective C2. The papers "Mesh Networks in Littoral Operations" (Benson et al. 2015) and the "Guide to Wireless Mesh Networks" (Misra et al. 2009) gave insight into both the fundamental operational uses and the technical aspects of mesh networks.

The CRUSER workshop provided an in-depth review into new technology development within and outside of the government. Briefing subjects included Additive Manufacturing by Kevin Reynolds of NASA Ames Research Center, Electronic Maneuver Warfare (EMW) by CDR Mark Coffman of Naval Warfare Development Center (NWDC) and U.S. Fleet Forces Command (USFFC), DARPA Collaborative Operations in a Denied Environment (CODE) by Mr. John Cranney of Deep Space Instrumentation Facility (DSIF) Lab, among others. These briefs gave SEA23 a broader knowledge of available technologies and the implementation of these technologies into future operations. In addition, working in small groups on a project at the workshop afforded the students the ability to network with personnel from DOD labs, academia, and industry.

SEA23 become familiar with emerging naval tactics and doctrines. Three reports that were useful in developing a deeper understanding this were "The Cooperative Engagement Capability" from Johns Hopkins Applied Physics Lab, "Maritime

Operations in Disconnected, Intermittent, and Low-Bandwidth Environment” from the 18th International Command and Control Research and Technology Symposium (Lapic et al. 2013), and “A Tactical Doctrine for Distributed Lethality” by CAPT (Ret.) Jeffrey Kline from NPS.

D. SYSTEMS ENGINEERING PROCESS MODEL

Systems engineering and systems analysis are two critical domains necessary for this capstone project. First application of systems engineering principles was necessary in order to create a SOS. Next, application of systems analysis allowed for quantitative assessment into the overall design of the SOS. During the first quarter of the project development process, it was crucial for the group to decide which systems engineering process will best support the project. In Blanchard and Fabrycky’s *Systems Engineering and Analysis* outlines three primary models for guiding and understanding the systems engineering process.

The first model is the waterfall process model (Figure 2). The waterfall method moves from start to finish and receives feedback once the entire cycle is complete. Blanchard and Fabrycky identify one of the major flaws with using this model “when deficiencies are found, phases must be repeated until the product is correct” (Blanchard and Fabrycky 2011, 36). Issues will always arise when using the systems engineering process in the real world. The group considered this model unacceptable for the project because the model is too rigid and provides no flexibility. SEA23 understood that the appropriate model necessary for the project required flexibility and feedback throughout the entire project process.

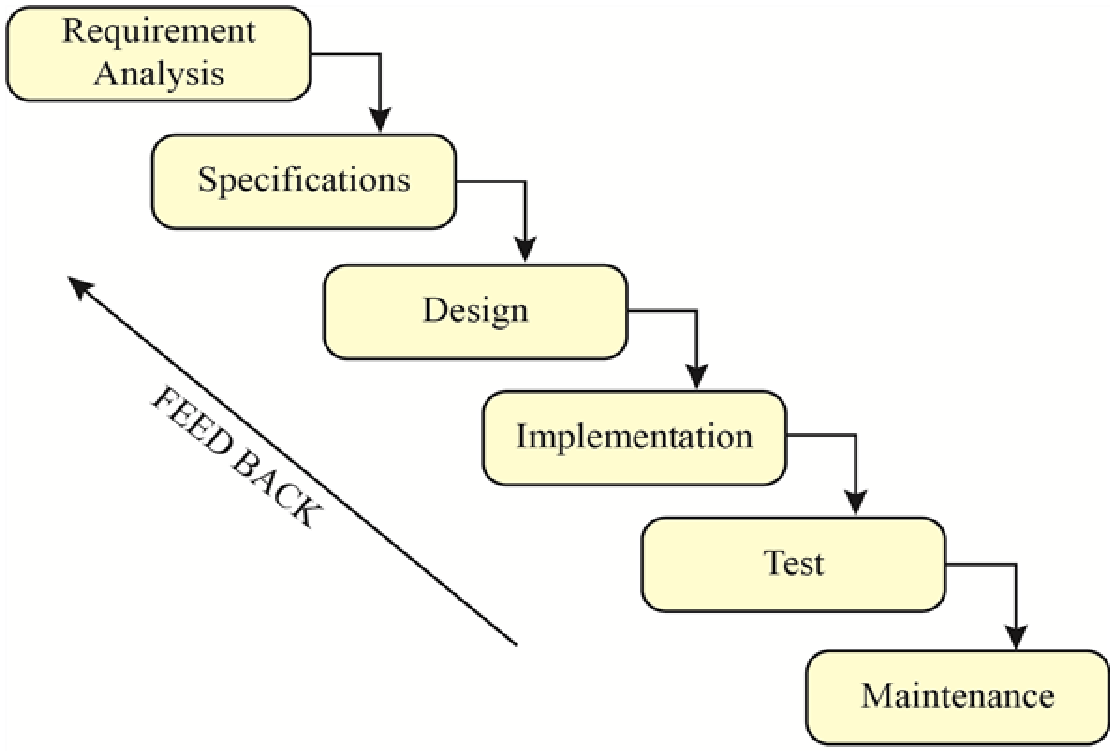


Figure 2. Waterfall Process Model. Adapted from Blanchard and Fabrycky (2011).

The second model was the spiral process model (Figure 2). The spiral model has built in feedback and is a more detailed than the waterfall process. According to Blanchard and Fabrycky, “the spiral process model allows for an evaluation of risk before proceeding to a subsequent phase” (Blanchard and Fabrycky 2011, 37). The spiral process model is useful when the requirements are, or the program is, relatively new. With proper management, the model receives constant feedback through each step of the process. The major downside with using the spiral method is that it is very time consuming. From one perspective, the spiral method will be appropriate for the project due to the broad scope and ill-defined requirements; however, the project timeline (three quarters, roughly nine months) dictated a less open-ended framework.

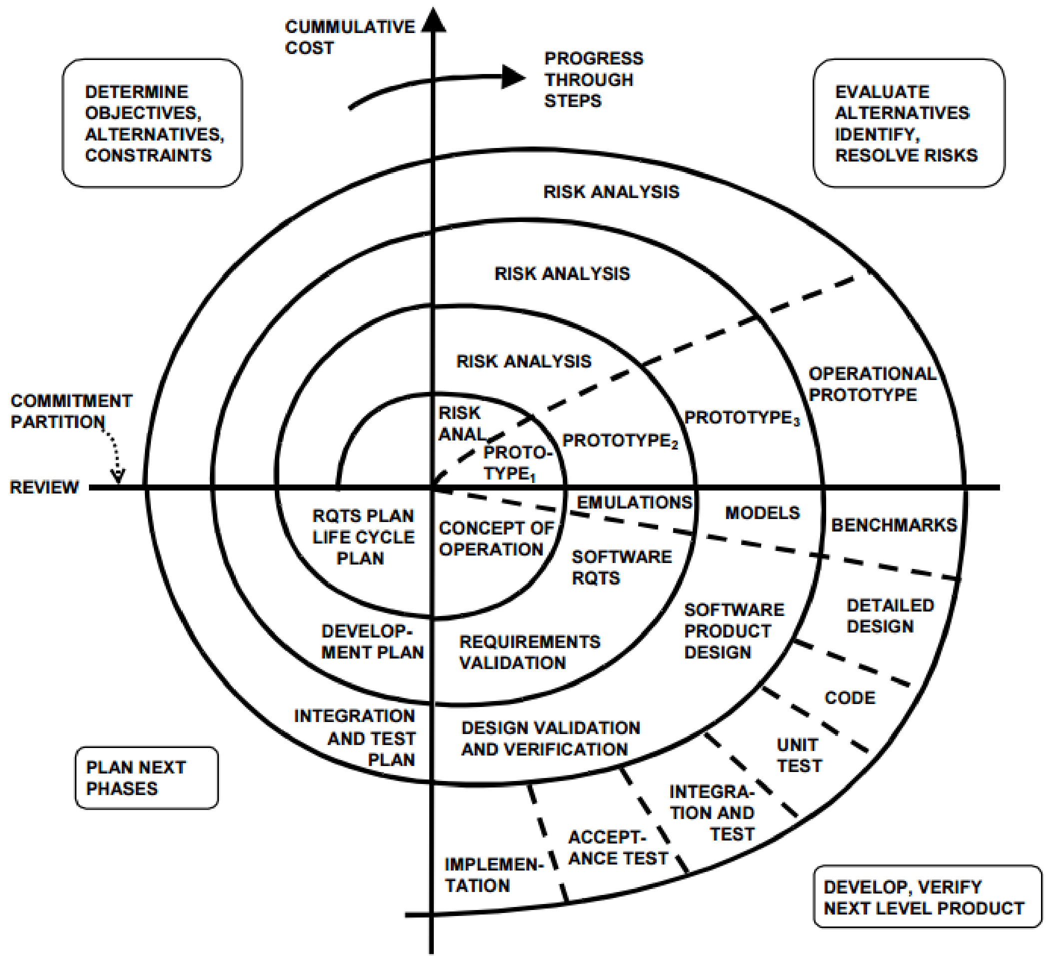


Figure 3. The Spiral Development Method. Source: Boehm (2000).

The third model examined was the “Vee” process model (Figure 3). It is a step process, like the waterfall model, but with built in feedback loops throughout the entire process. The “Vee” model splits into two parts: “Decomposition and Definition Sequence, Integration and Verification Sequence” (Blanchard and Fabrycky 2011, 37). It is also less time intensive than the spiral process model. The group determined that using a DOD approved model that also had built in feedback was be the most useful model for the project allowing a focus on the application of the systems engineering model components.

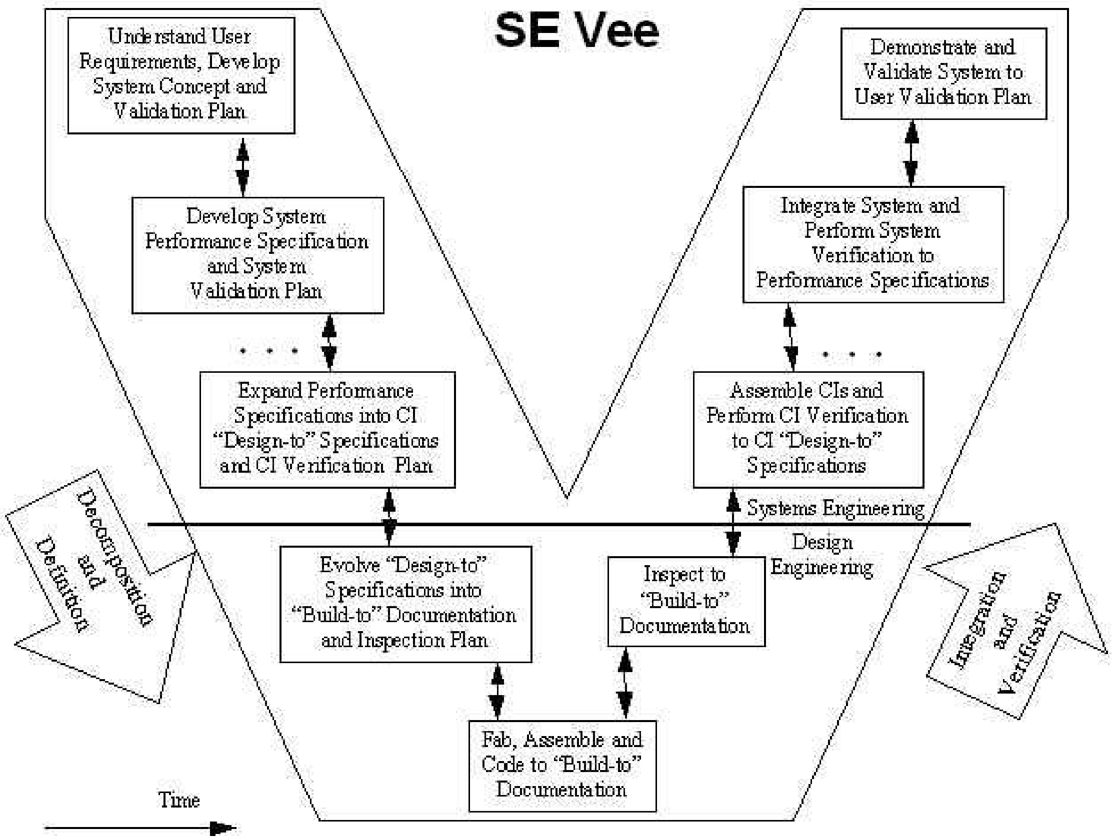


Figure 4. Systems Engineering Vee Model. Source Forsberg and Mooz (1992).

The "Vee" process model has seven distinct parts:

1. Stakeholder/Requirements Definition
2. Requirements Analysis Process
3. Architecture Design Process
4. Implementation
5. Integration
6. Verification
7. Validation

Stakeholder/Requirements Definition is the first step to refining the problem to a manageable size. The initial problem statement received from the project sponsor was broad and required discernment to identify the problem. The team conducted numerous

interviews with stakeholders and explored research avenues to analyze the initial problem statement and develop a more refined problem statement. Requirements analysis process consists of taking research and guidance from the stakeholders to decide which requirements the systems' need. Once determined, this information determines how to both qualitatively and quantitatively assess those requirements. Architecture Design Process involves developing functional decomposition, functional flow block diagrams, and using operational and system views from the selected architectural framework. Implementation is the development of the system, whether through designing or developing a concept of the operation (CONOPS). Integration is the process of bringing together the different aspects of the system into one coherent framework. Verification is using tools to see whether the system is functional or not. Tools used for verification include modeling and simulation, optimization, wargaming, and testing measures of performance (MOP) or measures of effectiveness (MOE). Validation ensures that the system meets requirements. Throughout this entire process, feedback loops provide continual checks to help ensure the meeting of requirements with the appropriate focus.

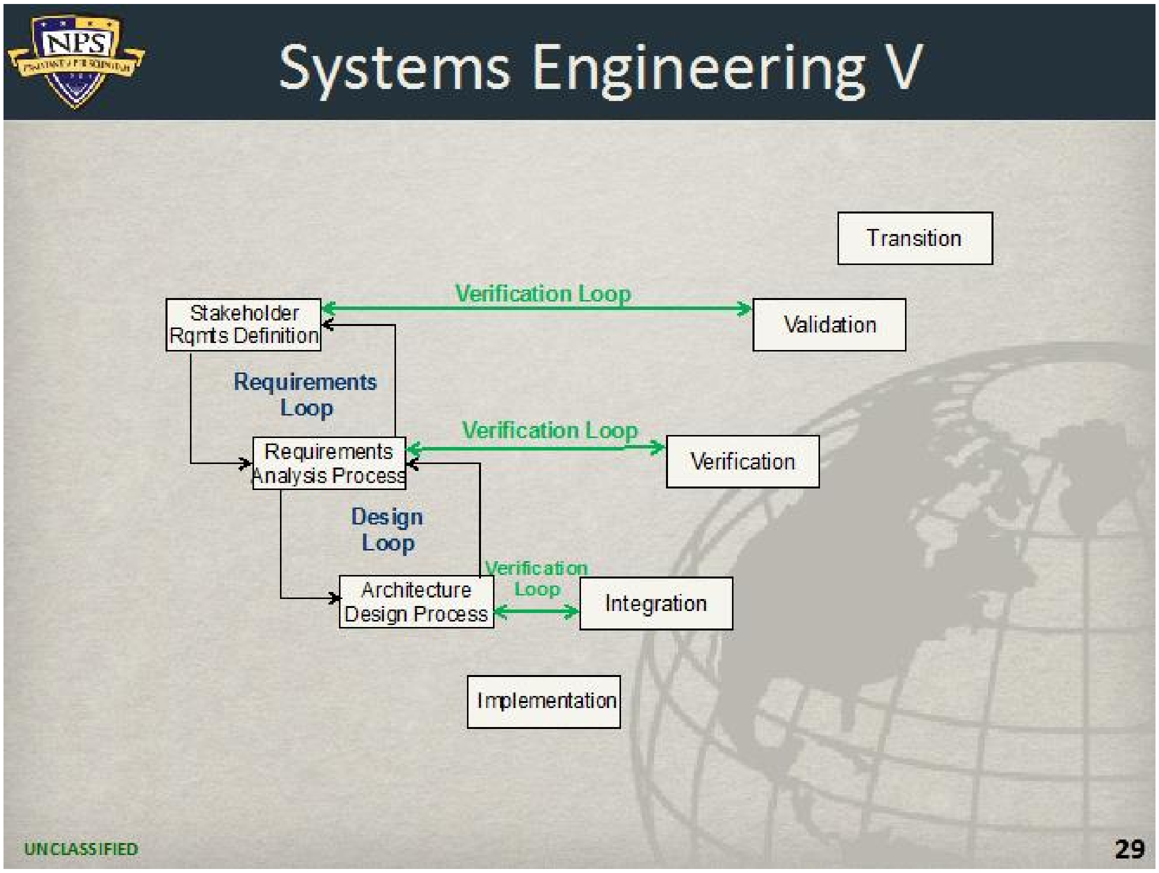


Figure 5. Systems Engineering V Model from SEA23 Final Progress Review Brief.

When examining the "Vee" process model, SEA23 identified that the majority of the project work will be on the left side of the "Vee" rather than on the right side (Figure 5) based on the rationale that the group was developing the SOS from scratch. Ultimately, the SOS will be theoretical with implementation of an analysis of alternatives using existing physical systems. The overall goal of this project was not to develop an actual physical prototype, but to create the framework that used to initiate a request for proposals (RFP) for operational use. As a result, much of the right side of the "Vee" will not necessarily remain relevant or appropriate to the overall project. With this understanding, the scope of the project will proceed from Stakeholder/Requirements Definition directly to Implementation. To utilize both sides of the "Vee," SEA23 shifted functions to verification and validation (normally completed during the implementation or prototype development phase). Figure 6 shows this shift.

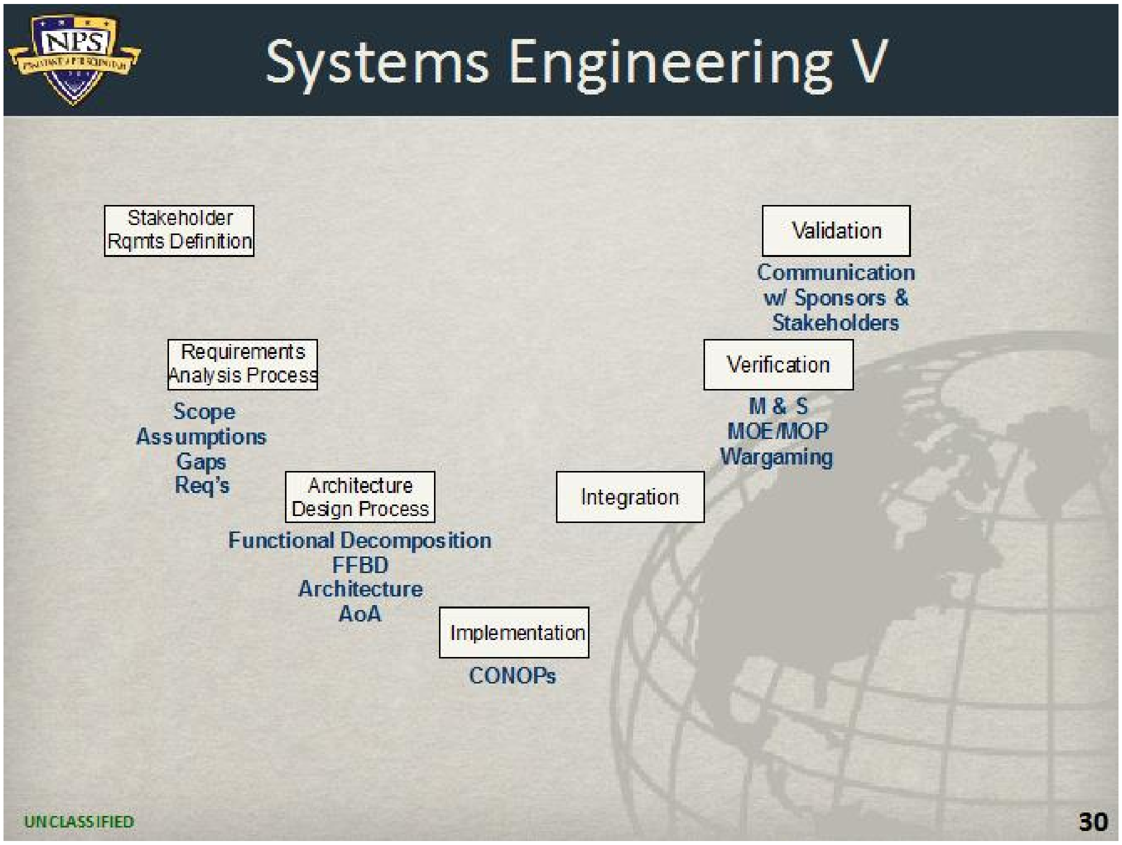


Figure 6. SEA23 Modification to the V Model from FPR.

After deciding on the "Vee" process model, SEA23 needed to pick an architectural framework. Maier and Rechtin's *The Art of Systems Architecting* (2009) identifies four standard architectural frameworks, defined as

> the U.S. Department of Defense Architecture Framework (DODAF), the Ministry of Defence Architecture Framework (MODAF), the International Standards Organization's RM-ODP standard, and the ANSI/IEEE 1471 Recommended Practice for Architectural Description for Software-Intensive Systems (now ISO 42010). All four use the basic concepts given above, but take different approaches to the selection of views, the models specified, and the overall approach to formalization and rigor. (315–316)

SEA23 decided on the DODAF approach for architecture development. First, because this is a DOD sponsored project, DODAF is an approved DOD process model. Second, SEA23 used DODAF throughout the Systems Architecting academic course providing a basic familiarity. SEA23 understood the operational and system views in

DODAF, how they related to each other, and their importance to understanding complex architecture development. Third, the software program used throughout the SEA curriculum, CORESIM, uses the DODAF architectural framework (Vitech 2016). These reasons led SEA23 to the conclusion that the DODAF framework was the best option for developing the systems architecture.

E. ORGANIZATION OF REPORT

Upon commencing the project, the team recognized that certain items would be required as a final report, to include requirements analysis, stakeholder analysis, and functional analysis. These items were determined through several means. First, SEA23 examined the "Vee" process model in greater depth. This helped the SEA23 to determine the general areas where it was necessary to develop products and the overall flow to developing those products through the process model. SEA23 used information from previous courses to determine the problem scope and the necessary analytical tools. This helped determine the flow and organization of the written report. The final written report mirrors the interim and final progress reports conducted for NPS students, faculty, and stakeholders. Finally, report generation came through an understanding of expectations, lessons learned, and feedback from previous cohorts of SEA final reports. The first three chapters of this report align with the first and second parts of the systems engineering "Vee" process model. Chapter I, "Introduction," lays out the beginning stages of the overall process identifying the project team members, project background, literature review, and the SE process that was used. All of this general information explains the background variables and reasoning behind SEA23's initial decisions. Chapter II "Need Analysis" is the first part of the "Vee" process model (Stakeholder and Requirements Definition). This section explains how stakeholders were determined and outlines the guidance they provided. Chapter III "Scope" examines our problem statement in depth and defines the boundaries of our problem statement. This is involved in parts one and two (Requirements Analysis Process) of the "Vee" process model.

The next three chapters (IV, V, and VI) cover the core products generated by the project. Chapter IV "Functional Analysis" contains functional decompositions, functional

flow block diagrams, and architectural designs. This covers portions of part two and part three (Architectural Design Process) of the process model. Chapter V, "Concept of Operations and Preliminary Design," consists of CONOP development, scenario specifics, and development of MOEs and MOPs. In the "Vee" process model, this covers portions of part three, four (Implementation), four (Integration) and five (Verification). Chapter VI "Modeling and Simulation" explains the models that were developed, the software, and the data produced. This covers chapters four, five, and six of the process model. The final three chapters (VII, VIII, and IX) are analysis. Chapter VII "Analysis of Alternatives" uses the data output from the models produced to examine a tradeoff of characteristics between several unmanned platforms. Chapter VIII "Cost Estimation" examines a cost relationship between the unmanned platforms in Chapter VII. Chapter IX "Conclusion" explains the completed project results. Chapter VII, VIII, and IX all cover portions of parts five and six (Validation) of the "Vee" process model.

F. REPORT CONTRIBUTIONS

Distributed lethality is a developing and evolving concept within the surface warfare community. It allows a group of surface ships to operate in a contested environment with significant offensive lethality. The research and analysis conducted throughout this project provide significant enhancements and advantages to surface forces. Using unmanned platforms that are organic to the surface components allows for a distributed force to remain undetected and in a position to provide offensive capabilities, while reducing their overall EM signature and locations.

The Detect-to-Engage (DTE) sequence essentially requires three distinct parts. It requires a forward line of sensing (detection) platforms, a means to relay that information (to), and platforms capable of conduct offensive firepower engagements (engage). This project seeks to identify the "to" portion in the DTE sequence. SEA23 assumed that the detection and engagement pieces in the DTE sequence are accounted for (such as DARPA project injects, Surface Action Group (SAG) components) and as a result, this project's tasking centers on how to relay effectively information throughout a network of node unmanned platforms. This information relay constrains U.S. forces and is a gap in

capability. To remain undetected or unlocated, U.S. naval forces will need to constrain their use of the electromagnetic spectrum. This project seeks to provide a means for surface forces to conduct offensive operations while making it difficult for a potential adversary to locate them. While maintaining a forward line of sensor platforms, surface forces are able to integrate and operate with those sensor platforms using a SOS node information relay network. SEA23 called it the “fire web” or “kill web” concept as the SOS node network (unmanned platforms) is capable of exchanging and relaying the appropriate targeting information necessary for surface platforms to conduct offensive strike capability.

There are numerous avenues for additional information and additional manners in which this project can support forward deployed joint forces. Following the systems engineering process throughout this project, a significant scoping of the project was required to ensure solution generation, while meeting the strict time constraints. Chapter IX, “Recommended Future Analysis” identifies potential areas of further study and insight.

THIS PAGE INTENTIONALLY LEFT BLANK

II. NEEDS ANALYSIS

A. STAKEHOLDER ANALYSIS

One of the fundamental requirements for any systems engineering process is the identification and analysis of stakeholders. As a project gains complexity, particularly the associated system and the system of system components, the identification of stakeholders and the input from stakeholders becomes increasingly important to scope the problem. Stakeholders are personnel that have direct buy-in to the completion of a program. Scoping continues through the inputs received from stakeholders identifying the needs and requirements of the project. The architects of the system must ensure that the program meets the primary stakeholders' needs and addresses the concerns of secondary stakeholders. According to the "Guide to the Systems Engineering Body of Knowledge,"

> Stakeholder needs and requirements represent the views of those at the business or enterprise operations level—that is, of users, acquirers, customers, and other stakeholders as they relate to the problem (or opportunity), as a set of requirements for a solution that can provide the services needed by the stakeholders in a defined environment. Stakeholder requirements play major roles in systems engineering, as they:
>
> - form the basis of system requirements activities.
> - form the basis of system validation and stakeholder acceptance.
> - act as a reference for integration and verification activities.
> - serve as means of communication between the technical staff, management, finance department, and the stakeholder community. (SEBoK 2016)

Before stakeholder outreach and interviews, SEA23 generated a questionnaire for use when working with and interacting with potential stakeholder personnel. The Institutional Review Board (IRB) and the SEA Department Chair approved the list of questions (Appendix B). There were many stipulations on the specific types of questions that can be asked and the SEA group worked to ensure that the wording and direct questions were within the established parameters of the IRB to ensure the project focused

on system development and not human subjects research. Once approved, these questions formed a baseline for conducting research with potential stakeholders in seeking solutions for the prescribed problem statement. Each question listed in the IRB questionnaire was derived through a breakdown and understanding of the initial problem tasking statement.

B. STAKEHOLDER IDENTIFICATION

After receiving the problem tasking, SEA23 began to develop a list of stakeholders who will be influential on the project. This included numerous campus advisors, military personnel, and academic personnel who were located on the NPS campus (Table 2). They helped provide initial feedback and guidance for identifying further stakeholders and scoping of the project.

Table 2. NPS Stakeholders.

Name	Specialty
RADM Rick Williams, USN (Ret.)	NPS Chair of Expeditionary and Mine Warfare
CAPT Jeffrey Kline, USN (Ret.)	Operations Research Department
CAPT Charles Good	NPS Surface Warfare Officer (SWO) Chair
Dr. Fotis A. Papoulias	Systems Engineering Department
Dr. Michael Atkinson	Operations Research Department
CAPT Jeffrey Hyink, USN	Senior NPS Aviator
Dr. Dan Boger	Chair of Information Sciences Department

SEA23 then began additional outreach to potential stakeholders across the DOD. NPS stakeholders identified these persons and entities as potential resources for research and insight into the project. SEA23 split this group into either primary or secondary stakeholders. Organizations that directly influenced the initial problem statement were primary stakeholders, while secondary stakeholders came through the contacts received through interviews and feedback with NPS personnel. The original list of stakeholders that was developed included the personnel and organizations listed in Table 3 and Table 4.

Table 3. Primary Stakeholders (outside of NPS).

Name / Organization	Location
Sponsor: OPNAV N9I (Mr. Mike Novak)	Washington, DC
COMPACFLT N9 (Mr. David Yoshihara)	Pearl Harbor, HI
Commander, Naval Surface Forces (Distributed Lethality)	Monterey, CA / San Diego, CA
OPNAV N99	Washington, DC

Table 4. Secondary Stakeholders (outside of NPS).

Name / Organization	Location
Naval Sea Systems Command (NAVSEA)	Washington, DC / San Diego, CA
Naval Air Systems Command (NAVAIR)	Patuxent River, MD / San Diego, CA
Space and Naval Warfare Systems Command (SPAWAR)	San Diego, CA
Naval Integrated Fire Control – Counter Air (NIFC-CA) (PEO / IWS)	Washington, DC / Dahlgren, VA
Naval Surface and Mine Warfighting Development Center (NSMWDC)	San Diego, CA
Johns Hopkins University Applied Physics Lab (JHUAPL)	Baltimore, MD
Naval Air Warfare Development Center (NAWDC)	Fallon, NV
Naval Undersea Warfare Center (NUWC)	Keyport, WA
Naval Submarine Development Squadron (SUBDEVRON) Five Unmanned Undersea Vehicles	Silverdale, WA

Using the listed stakeholders, SEA23 identified specific personnel within those respective organizations with whom engagement regarding possible involvement, research, and insight will be valuable. Their feedback allowed SEA23 to determine how stakeholders might be able to support the project. To establish initial contact, Table 5 lists potential stakeholders emailed an introductory letter on 17 November 2015.

Table 5. Initial Correspondence (email) List.

Name	Organization
LCDR Dwan	NSMWDC, N5 (IAMD)
LT Josh Mills	NSMWDC, N5, AO
Mr. Burkholder	PEO IWS 7
Mr. Kreischer	PEO IWS 3
Mr. Rogers	COTF
Mr. Sokol	JHU APL
Mr. Johnathan Pino	JHU APL
LT TJ Stow	Fleet Forces Command (FFC)
LCDR Gahl	OPNAV N96
LCDR Taft	Lead IAM WTI, Dahlgren
LCDR Lewis	COMPACFLT NPS POC
LCDR Litchfield	NSMWDC Dahlgren
LT Boyle	NAWDC, N6 (E-2D)
Dr. Mary Ann Cummings	NSWC Dahlgren / NAVSEA / Orchestrated Simulation through Modeling (OSM) / NIFC-CA

The email provided a brief background and introduction to the SEA23 project and requested any additional information, research, and insight they might be able to provide. The SEA23 team wanted as much subject-matter-expertise as possible. The team provided two attachments with this email: a project summary with an OV-1 Operational View and the list of questions developed for IRB review. The email format ensured that the group stakeholder outreach remained consistent throughout the project.

> We write to establish contact for possible guidance in the Naval Postgraduate School (NPS) Systems Engineering/Analysis (SEA23) capstone project. As a cohort of students, we have been trained and educated in the SEA pipeline throughout our time at NPS and the final project serves as our research thesis.
>
> Our project's purpose is to explore a system-of-systems capable of allowing cross-domain operations in a contested area. The project focuses on supporting tactical offensive operations across domains (air/surface/ undersea/cyber) using unmanned/manned systems. Attached to this email is the project tasking information.
>
> We are looking for potential support in the realm of stakeholder research, insight, and support. Our tasking includes applying a systems engineering

approach to generate a system-of-systems architectural design to support joint U.S. forces in a highly contested environment. An initial scenario for tackling this project focuses directly on the A2AD environment used to deny U.S. forces access into a very broad and diverse area.

Any insight you might have to support our capstone project would be greatly appreciated. If there is an alternative point of contact you can suggest, we would appreciate your recommendation. Thank you very much for your consideration.

C. STAKEHOLDER FEEDBACK

Stakeholder feedback was numerous throughout the project. SEA23 received it in two periods of outreach: the first in November 2015 and the second outreach in January 2016. Feedback varied leading to the addition and removal of potential stakeholders. The feedback helped to scope the list of stakeholders and provided SEA23 with specific points for research. Many responded with alternate points of contact helping to identify specific SMEs who can provide support. Responses from the initial outreach are in Table 6 with the second set of responses in Table 7.

Table 6. Initial Outreach Responses (November 2015).

Name	Organization / Feedback
LCDR Dwan (NSMWDC)	Feedback on the applicability of this project to future warfighting and integration.
LT Josh Mills (NSMWDC)	Feedback on numerous areas for research and other stakeholders that can support our research.
Dr. Looney (USFF N802)	Feedback on NIFC-CA and possible relation to our project, particularly integrated fire control relay.
LT Steve Perry (NSMWDC)	Feedback on numerous areas for research and other stakeholders that support.
Mr. CJ Toombs (NAVAIR China Lake)	Heimdall overview and SE approach to unmanned systems integration for sensors, C2, and communications
LCDR Gahl (OPNAV N96)	Primary point of contact (POC) for items related to stakeholders in OPNAV (NPS liaison). Introduced team to numerous members of NIFC-CA working group (Aegis, CEC, IAMD, SM-2, C2)

(continued on next page)

Table 6 (continued)

Name	Organization / Feedback
LCDR Lewis (COMPACFLT) / CDR Smith (COMPACFLT N9WAR) - UXS	Feedback on potential capabilities of unmanned systems integration into future operations to include testing/scenarios through various underway exercises.
Dr. Mary Ann Cummings (NSWC Dahlgren)	Modeling Distributed Lethality (wargaming) and use of unmanned systems in the model. Feedback on NIFC-CA interoperability and integration.

Table 7. Second Outreach Responses (January 2016)

Name	Organization / Feedback
LCDR Dwan (NSMWDC)	Feedback on the applicability of this project to future warfighting and integration.
LT Josh Mills (NSMWDC)	Feedback on additional stakeholders, particularly DARPA.
Dr. Looney (USFF N802)	Feedback on NIFC-CA and possible relation to our project, particularly integrated fire control relay.
LT Steve Perry (NSMWDC)	Feedback on numerous areas for research and other stakeholders that support.
Mr. CJ Toombs (NAVAIR China Lake)	Heimdall overview and SE approach to unmanned systems integration for sensors, C2, and communications
LCDR Gahl (OPNAV N96)	Increased correspondence for stakeholders inputs in OPNAV. Feedback concerning our products and paths forward.
LCDR Sandomir / LTJG O'Keefe (OPNAV N96Z / CRIC)	Direct feedback on application of a SOS information relay system for enabling distributed lethality. Provided feedback on products and ways-ahead for overall project
CDR LaPointe /Mr. Chris Delmastro (DASN UXS)	Significant feedback on integration of unmanned systems into naval operations including limitations and constraints.
Mr. Horvath / Mr. Herbert (OPNAV N99)	Significant feedback on SEA23 products and valuable input for way-ahead of project.
Dr. Galambos / Dr. Sam Earp / Mr. Neidlinger (DARPA)	DARPA feedback for ongoing on future projects for incorporation into the "forward line sensors" of the SEA project. CDMaST / TERN / ACTUV

D. STAKEHOLDER INTERVIEWS

A research trip taken in December to the Washington, DC, area for meetings with OPNAV N96, OPNAV N96Z, NSWC Dahlgren, OPNAV N99, and DASN Unmanned Systems (UxS) resulted in additional stakeholders added in January 2016. This trip allowed SEA23 to make personal connections with potential stakeholders. A second trip occurred during late February 2016. During the February trip, SEA23 met with stakeholders to outline and receive feedback on the current path to a solution. During the same travel period, interactions on campus continued. The following describes the information exchange with those stakeholders who provided the greatest feedback for scoping the direction of the project.

Commander, Naval Surface Forces (CNSF): The primary representative from CNSF was CAPT Charles “Chuck” Good who holds the Surface Warfare Officer Chair position at NPS. He is directly responsible for the collective of surface warfare officers on campus and serves as the direct liaison between the surface community and research at NPS. Through interactions and engagements with CAPT Good, the SEA23 team obtained direct feedback relating to the immediate impact to the surface community. Additionally, greater understanding of surface tactics and surface capabilities helped identify gaps and weaknesses for research. CAPT Good provided feedback tailored towards the direct applicability and feasibility of system components on individual unmanned platforms and relevance to the surface warfare community. Major feedback focused on detailed insight leading to research avenues for the SEA23 project, particularly for understanding the system of systems and the network components. For example, how does the system of systems “speak” to surface ships and integrate data exchange with surface ships. Understanding this provided greater insight into tactical data links: how they integrate, and how they operate with unmanned systems. Finally, he identified various limitations and constraints of unmanned systems integration for surface platforms.

OPNAV N96 / N96 (Z) (Director Surface Warfare / Distributed Lethality Task Force): The primary representatives from OPNAV N96/N96Z were LCDR Chris Gahl and LTJG Christopher O’Keefe. They provided feedback and support for distributed lethality and how the project enhances the distributed lethality construct. Suggested areas

for research exploration were graceful degradation of systems, line of sight communications, and mesh networks. Additionally, the overall system shall focus on a reconstitutable system of systems, with unmanned node platforms capable of organic launch from surface ship platforms. The goal for the system of systems was to enhance distributed forces and lethality of forces in the surface force strategy. Application of the system of systems to an adaptive force package can help in integration and fleet practices. Finally, the suggestion was made that operational applicability can increase if the capabilities and architecture components of the Naval Integrated Fire Control-Counter Air system were used on much smaller, agile, platforms (without the need for a nuclear carrier and E-2D Advanced Hawkeye command and control aircraft.

Deputy Assistant Secretary of the Navy for Unmanned Systems (DASN UxS): The primary representative from DASN UxS was CDR Cara Lapointe (Program Executive Office Ships, PMS 320). The DASN UxS office focuses on the future integration of unmanned systems into naval and military operations seeking to identify how unmanned systems can augment the role of current manned systems. One of the key goals for the employment of unmanned systems is to create an "organic away game" for distributed forces (ships) with the ability to have the full-scale coverage that a CVN provides, without the need for a CVN. They identified a capability gap that focuses on minimizing the overall "lag" time to the decision maker and the decision-making process and decision-making relay chain. By pairing manned-machine assets, focusing on increasing the speed of phases in war, decreasing the "pausing" time, and understanding how unmanned systems fit into the greater architecture picture, enhancements are possible. In the systems engineering process for unmanned systems integration, it is imperative that numerous iterative processes focus on the verification/validation/ accreditation as the future of unmanned systems continue to evolve. Research shall focus on identifying a global versus local framework and the effects and impacts of or to system degradation. A key to understanding unmanned systems are the physical domain interfaces—transition and cross-over points for relay of information from unmanned systems (i.e., tactical data link—how does the unmanned system "talk" to the ship?)

Office of the Chief of Naval Operations N99 Directorate for Unmanned Systems (OPNAV N99): The primary contacts at OPNAV N99 were CAPT Joe Horvath (USN, ret.) the Deputy for Rapid System Development and Mr. Gary Herbert. An immediate input point was to focus on line of sight communications and improving NIFC-CA through unmanned systems. OPNAV N99 first raised awareness and provided insight into the concept of denied, degraded, intermittent, and low-bandwidth (DDIL) environments and operating constraints within an A2AD construct. They desired to increase the operational capability of the Cooperative Engagement Capability (CEC). The framework of the system of systems shall focus on the components of agility and resiliency. OPNAV N99 recommended adjustment of the project to focus on the minimum requirement of UAV node platforms and not specific available systems. This is accomplished by exploring a different problem space and working to investigate the full scale of cross-domain operations. Additionally, focus shall include information relay and information sharing between unmanned systems.

DARPA (Defense Advanced Research Projects Agency): The primary representatives from DARPA were Dr. Jim Galambos (Program Manager Strategic Technologies Office (STO)), Mr. Rick Neidlinger (DARPA STO Maritime/Aviation Support) and Dr. Samuel Earp (DARPA STO). Their feedback focused on using components of numerous DARPA related research and inputs for technical injects and forward-looking sensor platforms (TERN) in the systems engineering analysis architecture and construct. The Cross Domain Maritime Surveillance and Targeting (CDMaST) (Figure 7) project aligns well with the SEA23 research. It was determined that understanding the full Detect-to-Engage (DTE) sequence was imperative to identifying weaknesses/vulnerabilities in the U.S. ability to conduct offensive operations. DARPA was able to provide feedback that helped inform the system of systems constraints and limitations. Additionally, many different concepts were suggested for further exploration including architecture, requirements, constraints, unmanned versus manned systems, cost restraints, data relay, concept of operations, “kill web,” measures of effectiveness, and measures of performance. The DARPA representatives suggested that SEA23 differentiate between the optimization of the individual node systems and the

optimization of the system of systems network. Separating the two is best to ensure understanding the intricacies, limitations, constraints, and capabilities of the network versus the platforms.

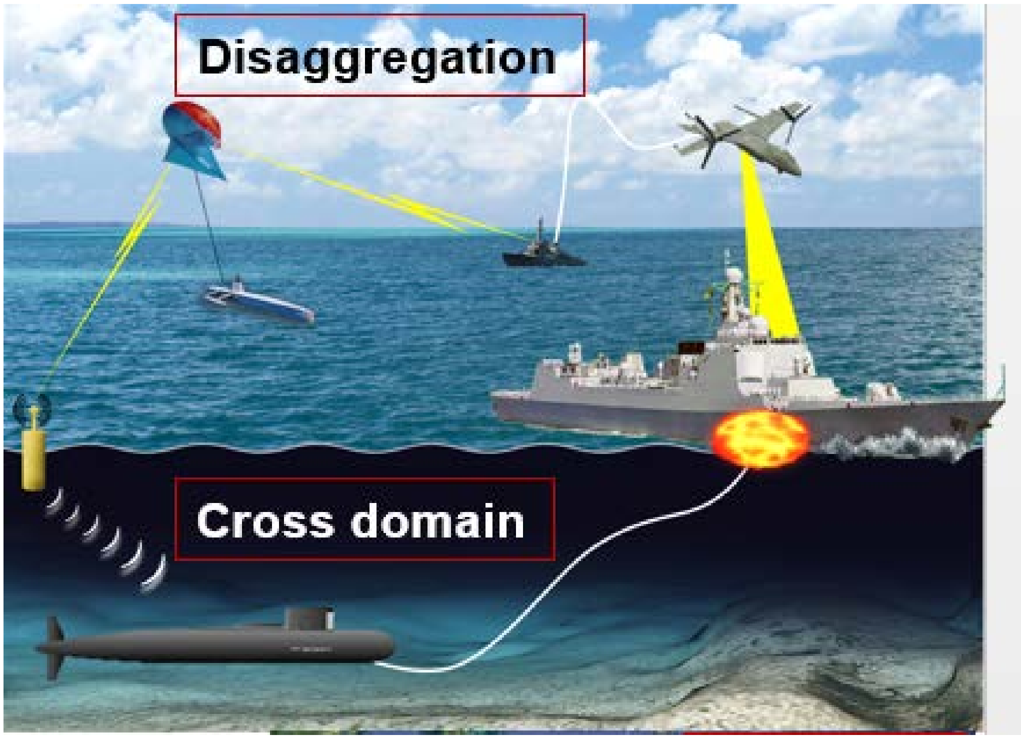


Figure 7. Cross Domain Maritime Surveillance and Targeting (CDMaST) Conceptual Drawing. Source Galambos (2016).

Naval Surface and Mine Warfare Development Center (NSMWDC): The primary representatives from NSMWDC were LT Josh Mills and LT Steve Perry. NSMWDC focuses on reinvigorating tactical excellence in the surface warfare community through the development and adoption of enhanced surface warfare tactics. They provided greater fidelity on distributed lethality and NIFC-C. NSMWDC writes and validates naval doctrine and tactics for the fleet, which helped SEA23, identify current challenges, constraints, and requirements. An area suggested for future research is integration of the P-8 Poseidon maritime patrol and reconnaissance aircraft as an information relay within the system of systems. They also advocated the use of establishing mobile ad hoc mesh networks. Exploration into these areas, particularly for

requirements, will be substantial in providing a way forward for future technological integration.

NPS Chair of Mine Warfare, Systems Engineering, RADM Rick Williams (USN, Retired) works directly with mine warfare and undersea warfare systems at NPS. RADM Williams explained student research at NPS and its support to naval operations. Additionally, he reviewed the necessary systems engineering components for determining specific information for platforms. RADM Williams emphasized the expectation of degradation for positioning, navigation, and timing capabilities, but not their total loss when operating in South China Sea and an A2AD environment. Systems engineering shall focus on the range, size, and weight constraints of systems, as well as the limitations associated with those requirements. For purposes of scoping and analyzing, he recommended identifying a single concept of operation and then viewing and reviewing that concept from multiple perspectives, addressing the questions: what assumptions were made? What modifications were made? What were the primary issues? What were the common issues? What are the capabilities and limitations in each domain? What are the major (or most common) constraints? By answering these questions and removing variables, SEA23 can adjust the scenario during problem development.

Stakeholder feedback and interaction, started early and, was pivotal throughout our project. Maintaining an open dialogue with stakeholders helped to provide feedback and insight ensuring that the team remained on track and aligned with stakeholders' requirements and needs. SEA23's analysis addressed the primary stakeholder needs driving the project and the developed solution.

THIS PAGE INTENTIONALLY LEFT BLANK

III. SCOPE

A. SCOPE METHODOLOGY

At their outset, most projects are too open ended for serious qualitative analysis and development. The SEA23 team's tasking was not atypical in this regard. Prior to any analysis, the team had to determine what the problem actually was and where its boundaries were. Placing boundaries on a project through in-depth discussions with the project's sponsor helps identify their actual goals and desired outcomes from the study. The sponsor often makes the problem statement as open ended as possible to allow the project team to determine the best approach for project completion. At times, the sponsor does not fully understand their problem. The team must present their determinations for the project's problem and their plan to solve it.

The project team had to limit the scope of their project based on the resources available to them at the time. These were time, funding, and personnel. Of these, time was a heavy influencer on what the project team was able to accomplish. Time constraints are not always a detriment to the project, as it requires a focus on developing and providing a product that is usable to the sponsor. SEA23 wanted to provide a solution that can join the fleet within the next 10–15 years. This allowed the team to focus on concepts and technologies that are currently in use in the fleet or will reach anticipated initial operation capability within that timeframe.

B. IN SCOPE

CAPT Jeffrey Kline (USN Retired), NPS' Systems Engineering Analysis curriculum chair and OPNAV N9I representative, in a memorandum dated 07 July 2015, presented SEA23's tasking:

> Design a fleet system of systems and concept of operations for employment of a cost effective and resilient unmanned and manned system capable of allowing cross-domain targeting information in a contested area in the 2025–2030 timeframe. Consider manned and unmanned systems in all domains to provide sufficient information to support effective tactical offensive operations by air, surface, undersea, and cyber. Explore how unmanned systems may contribute to cross-

> domain information exchange to support navy fires or to create an "all domain" naval integrated fire control capability to create an asymmetric warfighting advantage in a contested environment. Explore alternatives in adaptive self-governing communications networks from T1-like capability to a 'thin-line' getting the target coordinates through capacity. Consider employment requirements, operating areas, bandwidth, connectivity, interoperability, sensor data basing support in forward areas or from CONUS bases and joint contributions. Generate system requirements for platforms, sensors, and communications in a challenging EM environment. Develop alternative architectures for platforms, sensors, manning, command and control, intelligence collection/dissemination and consumption, communication and network connectivity, and operational procedures. Address the costs and effectiveness of your alternatives in mission areas like at-sea strike and electronic maneuver warfare.

From this statement, three key themes emerged from the problem statement: unmanned systems, cross-domain information exchange, and the concept of "all domain." During SEA23's first meetings, discussion focused primarily on what this meant. These were the first steps taken to determine the scope of the project. Using discussions with the project sponsors and through the cohort's own brainstorming, a focused problem statement emerged. SEA23 presented it to CAPT Kline prior to the initial interim progress review on 04 February 2016.

> SEA23 will investigate a concept of operations in a contested environment using modular unmanned and manned platforms capable of carrying communications and data suites to enable cross-domain targeting information in support of Tactical Offensive Operations (TOO) in a contested, denied, degraded, intermittent, and limited bandwidth (DDIL) environment. The focus areas that this updated problem statement identified are:
>
> - Cross Domain Targeting,
> - Tactical Offensive Operations,
> - Denied, Degraded, Intermittent, and Limited (DDIL) bandwidth environment,
> - Modularity. (Kline 2015)

The key to understanding why each of these areas is important starts with the operational environment. During military operations in the early 1990s, military operations began incorporating satellite communications (SATCOM), but they remained a member of the supporting cast, not a key pillar. Contrasting this with current military operations, SATCOM is an essential component to Command and Control (C2),

Intelligence, Surveillance, and Reconnaissance (ISR), and Positioning, Navigation, and Timing (PNT) (Lapic et al. 2013). With such reliance on satellites, it is not surprising that potential adversaries are testing methods for eliminating that element. In 2007, China successfully used land based missiles to destroy an aging satellite (Lapic et al. 2013). In light of this threat, the U.S. and her allies must look for ways to reduce dependence on satellite capabilities. SPAWAR calls this a shift in focus from ashore Network Operations Centers to the strike group afloat (Lapic et al. 2013). SEA 23's project tasking helps to support that shift.

1. DDIL and A2AD Environments

The DDIL and A2AD environments are of increasing concern to the U.S. and its allies. Broken into two parts, A2AD creates the situation where a force cannot move into a theatre or operate freely in an area due to enemy control (Tangredi 2013). This is not a new concept, but the methods for creating this environment have evolved throughout history. Five key pieces need to be in place for an adversary to create this situation according to Sam Tangredi in *Anti-Access Warfare*. These elements are defense against a superior adversary, role of geography, maritime domain as the conflict space, criticality of information and intelligence, impact of extrinsic events (to include DIME) (Tangredi, 2013). DDIL contributes to an A2AD strategy by affecting the information and intelligence available to a combatant. With the loss of the SATCOM link, the strike group must have an organic means of relaying information at ranges that place the units outside the reach of adversary shore based missile defenses. This range has increased in the past two decades from 70 NM to over 700 NM (Eckstein 2016). The combination of these elements makes the ability of naval operations in geographic areas, which have natural boundaries more difficult, such as bays or marginal seas (e.g., the South China Sea).

2. Cross Domain Targeting

Cross Domain Targeting is a concept that uses all available assets to conduct the range of operations encompassing a "detect-to-engage" sequence. In a contested DDIL and A2AD environment, naval vessels must avoid the use of electronic transmissions to prevent detection. This includes high-power radars and communications that can be either

detected or jammed. Other means of passing target information need to be available to the warfighter so they can remain effective while remaining undetected. Cross-Domain Fires aim to harness system of systems architectures to this effect. It allows the passing of targeting information between combatants like the Naval Integrated Fire Control-Counter Air while operating in a passive mode. DARPA describes it as a disaggregation of functions across multiple platforms (Galambos 2016).

3. Tactical Offensive Operations

According to the Naval Doctrine Publication 1,

> The tactical level focuses on planning and executing battles, engagements, and activities to achieve military objectives assigned to tactical units or task forces. Activities focus on the ordered arrangement and maneuver of combat elements in relation to each other and to the enemy to achieve combat objectives. (NDP1 2010)

The phrase refers to those maneuvers that occur in this level of war. For many years, the Navy has focused on defending against incoming threats, but with re-arming and emerging peer competitor navies, there must be a shift towards taking the fight to the enemy and tactical offensive operations is an effort to re-emphasize this. Tactical offensive operations are in the category of power projection, which "includes a broad spectrum of offensive military operations to destroy enemy forces or logistic support or to prevent enemy forces from approaching within enemy weapons range of friendly forces" (NDP1 2010).

4. Modularity

As defined by *Webster's*, when something is modular it is "having parts that can be connected or combined in different ways" (Webster's Dictionary, 2016). SEA23 applies this concept to both the individual units in the system as well as to the system of systems. The team intends that the mission payload will be self-contained and usable in, or on, any number of platforms, both manned and unmanned, thus the modular design. This concept then persists to the system of systems that has a modular "plug and play" capability where available assets can form ad hoc networks to communicate and relay

data. This modularity creates a flexible system of systems that has self-healing characteristics to maximize network availability with these characteristics:

- relay of "target quality" data
- line-of-sight communications
- system of system mesh network architecture
- minimization of the use of manned assets
- data throughput

C. OUT OF SCOPE

Through a similar process, SEA23 identified and bounded what the study does not cover. The team based these boundaries on what they could accomplish during the project's timeframe and what capabilities are already in existence. The primary boundary imposed on the project was that it would focus only on the communications relay element, not the detection or the engagement pieces. The focus will be on the "to" of the detect-to-engage sequence. Past and future projects have been dedicated to discussing and studying both detection and engagement, and it was determined that including them will create too broad of a study.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. FUNCTIONAL ANALYSIS

Functional analysis of system requirements begins with identifying the design criteria that allows the system to perform its mission. It starts with analysis of system requirements that results in identification of top-level system functions. Decomposing these further decomposed identifies component design criteria and constraints. Functional architecture development uses functional flow block diagrams (FFBD) that integrate and align the functions needed to form the functional baseline of the system (Blanchard and Fabrycky 2011, 100).

SEA23 selected a team with expertise on the systems engineering and systems architecting processes. The team identified that the communications network must integrate into existing systems due to initial operational capability of 2025 to 2030 because today's systems will still be in service at that time. The Huynh and Osmundson System of Systems Architecture Development Process (SoSADP) model was used to develop the system architecture and for verification and validation using modeling and simulation (Figure 8). This model identified critical components for completing the architecture and assessing its performance through modeling and simulation.

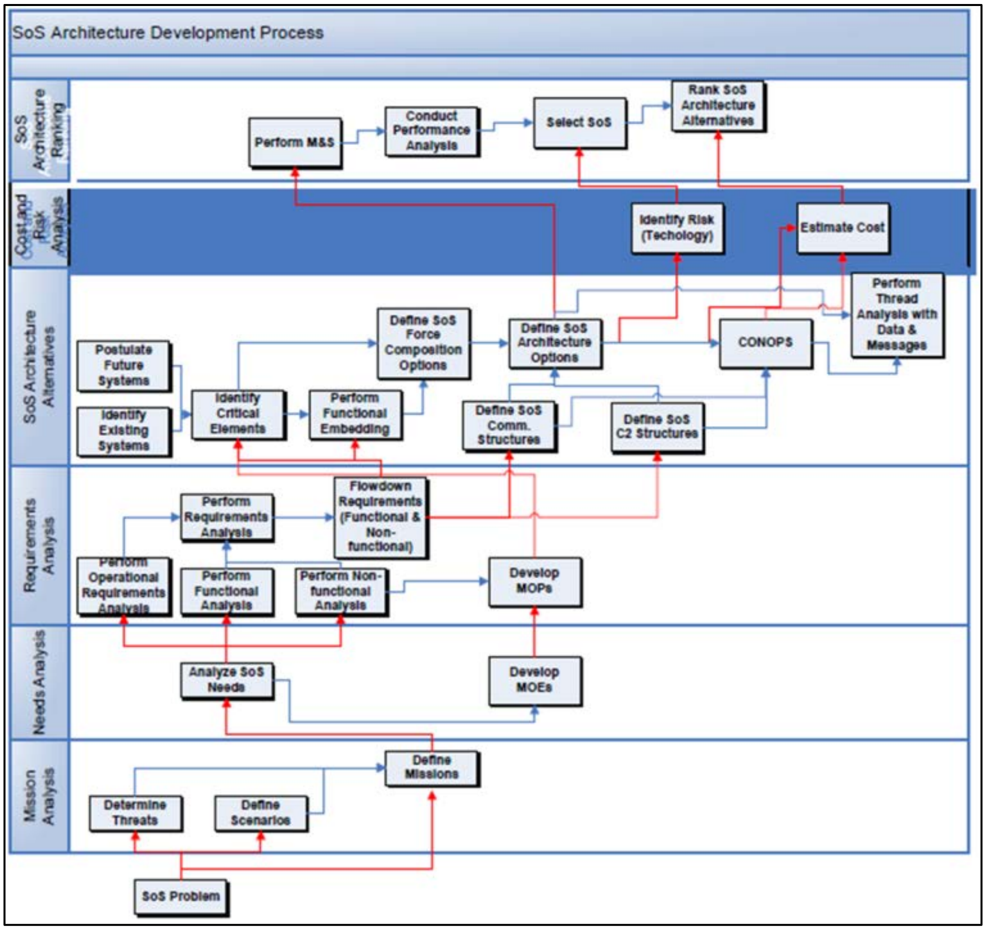


Figure 8. The Layered Structure of the SOS Architecture Development Process (SoSADP). Source: Huynh and Osmundson (2007).

A. ARCHITECTURE

A system architecture provides the high-level design of a system addressing stakeholder needs, ensuring all components and subsystems work together, and explaining the trade-offs required to meet stakeholder needs. The system architecture visually communicates the system design to stakeholders, confirming stakeholder needs while also simplifying complex systems. Rechtin and Maier (2009) describe architecture as, "The structure in terms of components, connections, and constraints—of a product, process, or element" (415). The International Council on Systems Engineering (INCOSE) defines systems architecture as, "The fundamental and unifying system structure defined

in terms of system elements, interfaces, processes, constraints, and behaviors" (Maier and Rechtin 2009, 417)).

The architecture for the unmanned system relay network is important in illustrating how the system processes and interfaces help to complete the mission. It helps define the constraints the SOS will have while conducting the mission. Critical operational issues (COI) that will affect the capabilities of the system can be determined during the development of system architecture. The DODAF is able to relate to the steps of the Huynh and Osmundson SoSADP model used by the team. SEA23 started with Vitech's system engineering software, CORE, for system architecture development, but it was not adequate in facilitating a team based architecture design process (Vitech 2016). For this reason, SEA23 decided to use Innoslate, a systems engineering and requirements tool developed by SPEC Innovations, for the design of the system architecture because of its Internet-based collaborative environment and built-in DODAF product templates (SPEC Innovations 2016). Innoslate allowed access for all team members to update and make changes to the DODAF products.

B. ANALYSIS OF TASKING STATEMENT

The tasking statement determined key areas to decompose for requirements development. The analysis focus areas from the tasking statement are:

- exchange cross domain targeting information,
- support tactical offensive operations,
- use of manned and unmanned systems.

Exchange of cross-domain targeting information is a key focus area because this capability allows the SOS to receive and transmit target data from any domain. Supporting effective tactical offensive operations gives the SOS the capability to engage the targets contained in the targeting information. Finally, SEA23 selected the use of manned and unmanned systems as another key focus area to show that the SOS can consist of both types. Identifying these areas allowed the analysis and decomposition of the functions associated with each key focus area.

C. OPERATIONAL VIEW-1 (OV-1)

The OV-1 is the High-Level Operational Graphic within DODAF (Figure 9). The OV-1 is a pictorial representation and describes the scenario concept. It conveys the scope and context of the architecture to the decision maker. The OV-1 had multiple iterations throughout architecture development. The final OV-1 may not be produced until after the system architecture is complete (DODCIO 2010).

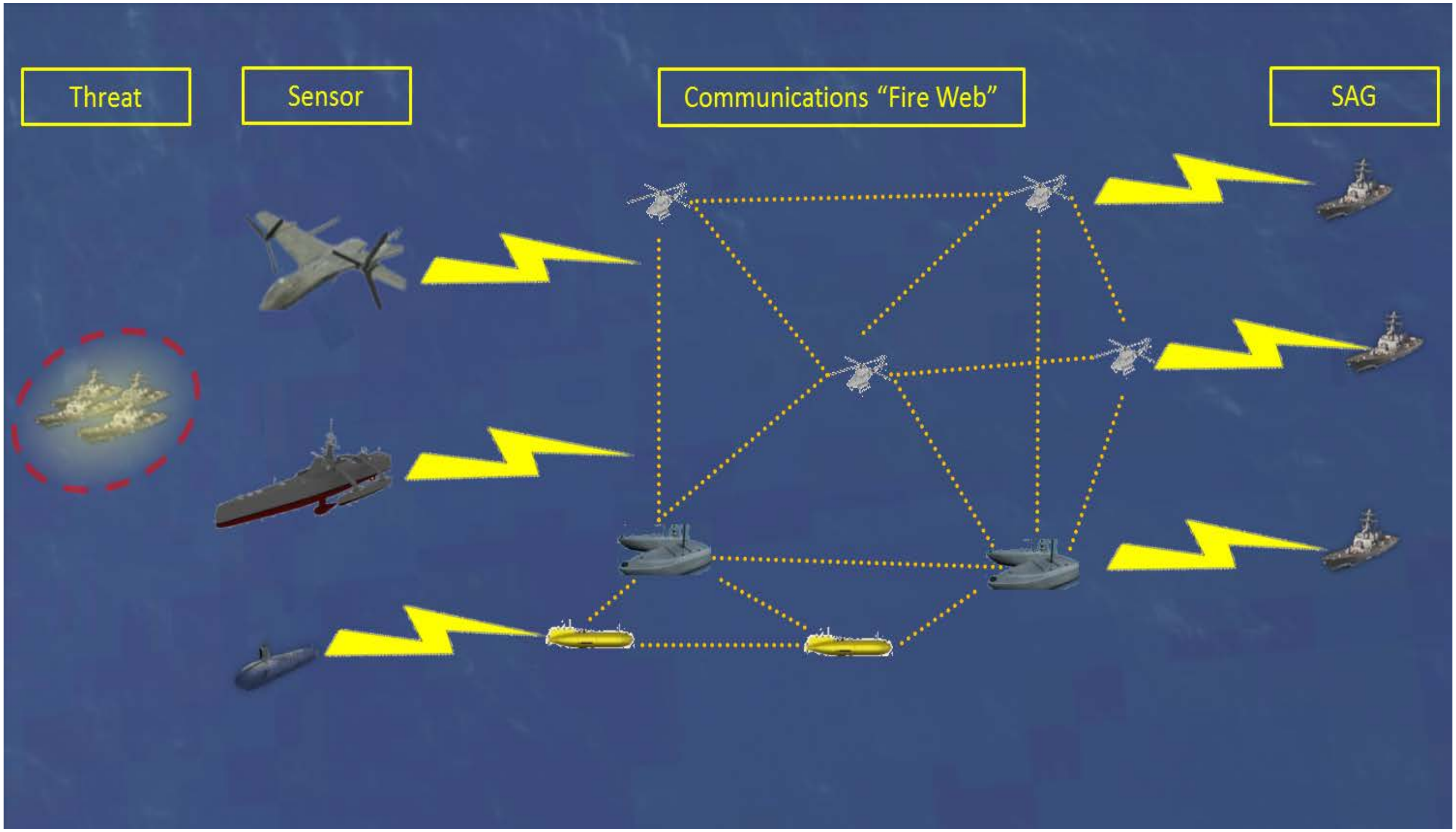


Figure 9. High-Level Operational Concept Graphic (OV-1).

The OV-1 supports interoperability between platforms to enable line-of-sight (LOS) communication and information relay. The unmanned vessels (UxV) "Fire Web" receive an input from a domain sensor (such as pictures, radar information, or video). The UxV "Fire Web" is then able to transmit the message across the various UxV platforms until it can output the information to a ship within the surface action group (SAG) or command and control (C2) element. Information from the SAG or C2 element can also send information to sensor platforms through the UxV "Fire web." The problems' scope extends to the reception of targeting information from a sensing node to its communication to the SAG through the "Fire Web."

D. FUNCTIONAL DECOMPOSITION OF KEY FOCUS AREAS

SEA23 decided that the most effective decomposition uses the Universal Naval Task List (UNTL) to identify the operational tasks needed to conduct Communications, Intelligence, Surveillance, and Reconnaissance (CISR) (OPNAV 2007). The team used the UNTL to identify the lower level tasks that went into the operations of CISR. CORE architecture software helped develop this functional decomposition. The decomposition assisted SEA23 in scoping the problem to design a system of systems to send effective targeting communications "over-the-horizon" through organic and unmanned means.

SEA23 used the temporal view operations template for an air interdiction operation from the UNTL in the initial phases of the functional analysis and decomposition of the system requirements to support tactical offensive operations. This template offered an illustrative view of the sequence of tasks that are necessary when conducting air interdiction. SEA23 realized that not all tasks are required for the CISR requirements of the system and determined that Assemble Forces in the Joint Operations Area (OP 1.2.3), Prepare Plans/Orders (OP 5.3.9), Collect Target Information (NTA 2.2.1), Transmit and Receive Information (NTA 5.1.1.1), and Provide Intelligence Support to Targeting (NTA 2.4.5.5) are the tasks associated with CISR (Figure 10).

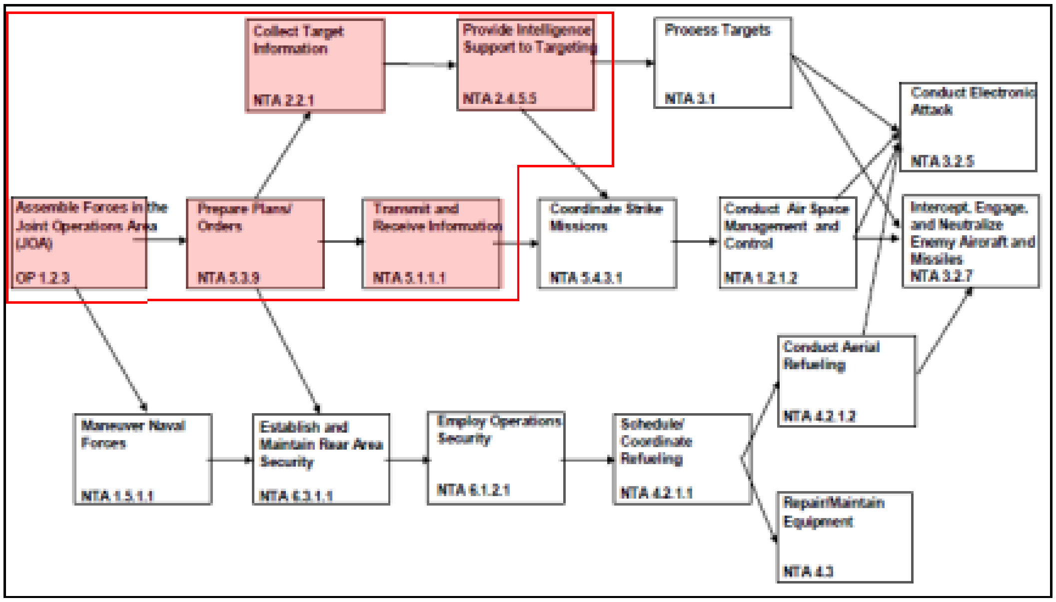


Figure 10. An Operations Template for an Air Interdiction Operation Used for Functional Decomposition Adapted from: OPNAV (2007).

SEA23 found that CORE allows for development of detailed architecture frameworks but lacked collaboration capability (Figure 11). A new functional decomposition used Innoslate, which revealed that the functions of CISR were outside the requirements from the tasking statement. Although the initial decomposition did not provide a good functional baseline for the system, it did provide critical insights to scope the problem. It was determined that the problem was the transfer of targeting information from a sensor to a command and control (C2) element and then information back to the sensor or shooter. The manned and unmanned systems were the platforms that will provide the means to transfer the information. Using unmanned systems for targeting information transfer helped meet the goal of reducing risk to manned platforms while operating in a contested environment. Therefore, the top-level function that the SOS needs to perform is Employ Remote Vehicles (NTA 1.1.2.5).

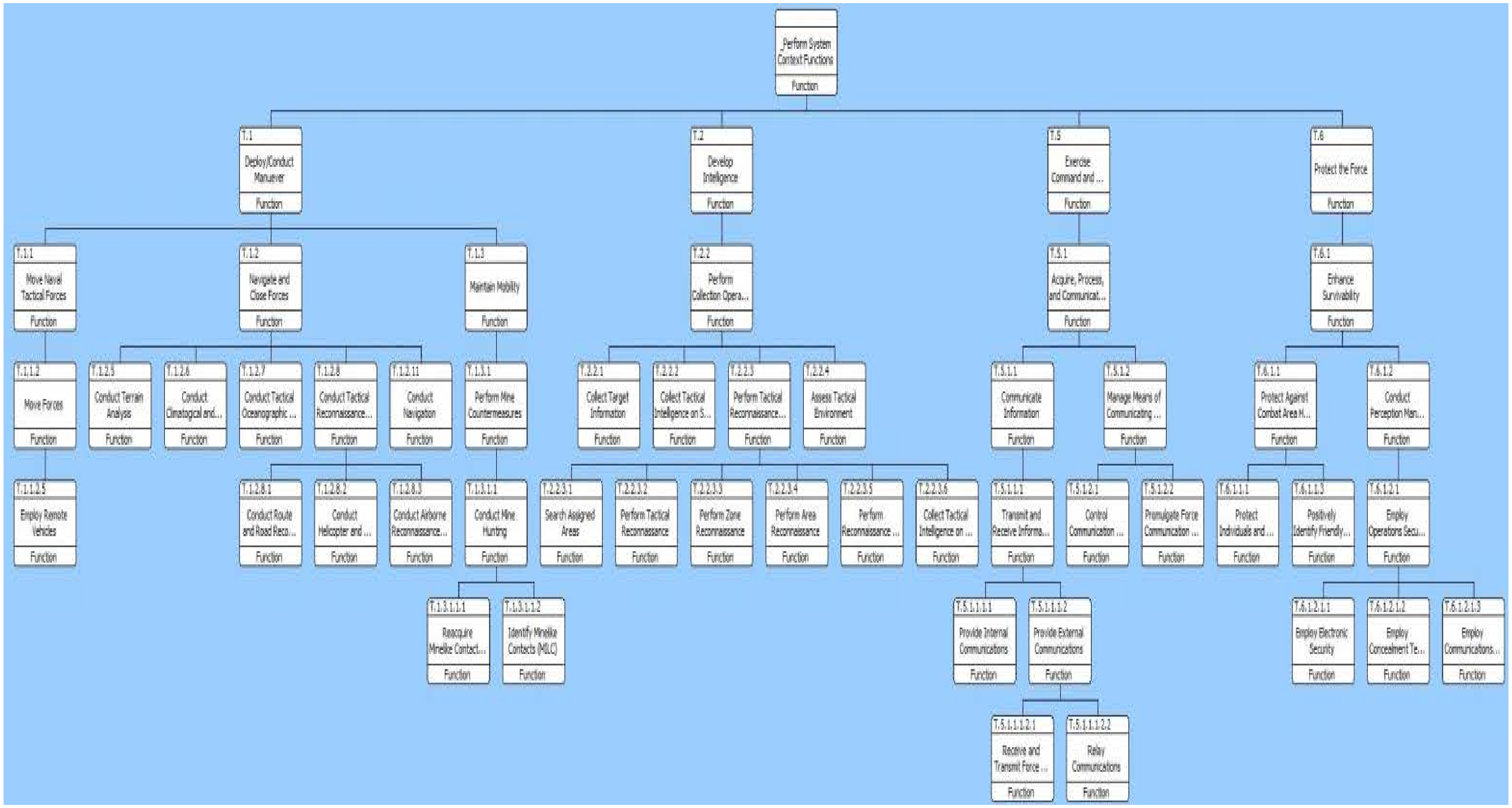


Figure 11. Initial Functional Decomposition Based on the Operations Template for Air Interdiction Operation.

E. OPERATIONAL ACTIVITY DECOMPOSITION (OV-5A)

The DODAF OV-5a functional decomposition is the Activity Decomposition Tree. It describes the breakdown of high-level activities (i.e., functions) into low-level activities and is useful as an aid for the development of the OV-5b also known as the functional flow block diagram (FFBD) (DODCIO 2010).

1. Top-Level Functions

The primary function of employ remote vehicles is "the operation of vehicles such as robots, drones, unmanned underwater vehicle (UUVs), unmanned aerial vehicles (UAVs), and other devices from a local control station" (OPNAV 2007, 3-B-7). The employment of remote vehicles requires the deployment, launch, operation, and recovery of the remote vehicle(s). These functions became the detailed functions that allowed for further decomposition of the task of employing remote vehicles (Figures 12 and 13). Appendix C lists these functions.

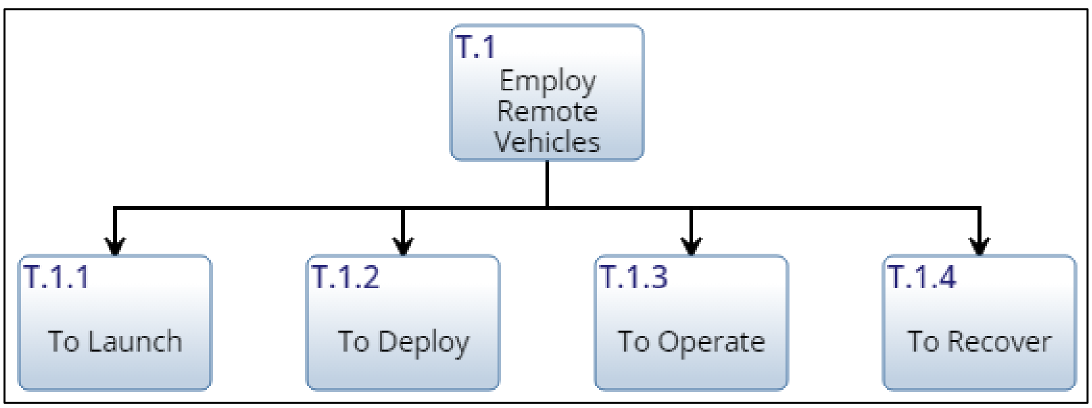


Figure 12. High-Level Functions of the Universal Naval Task List (UNTL) Task of Employ Remote Vehicles.

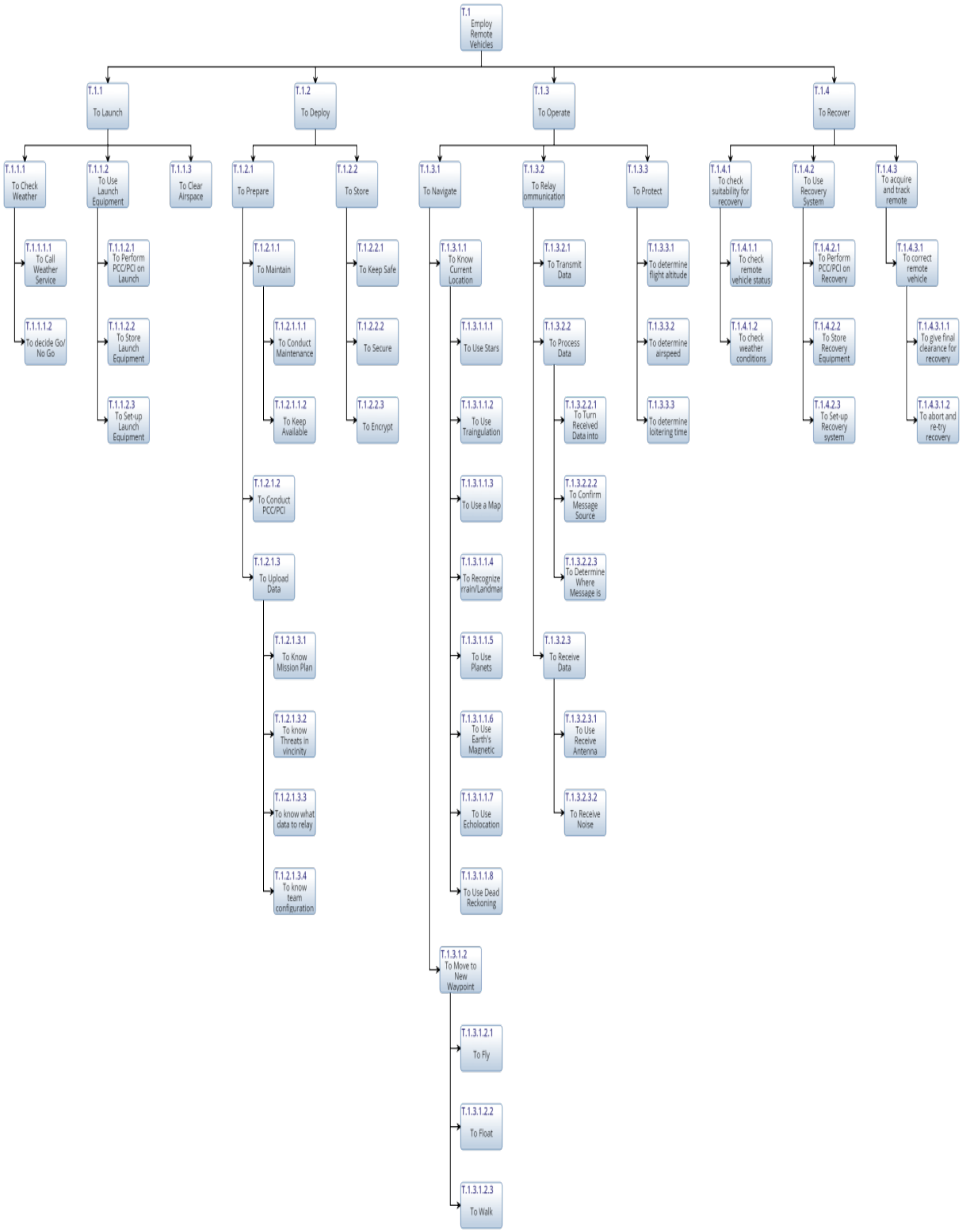


Figure 13. Functional Decomposition of the Universal Naval Task List (UNTL) Task of Employ Remote Vehicles.

2. Operational Activity Model (OV-5b)

The OV-5b is the Activity Model in DODAF that describes the operational flow of the functions conducted in order to accomplish a mission. It shows the connections between activities through resource inputs/outputs, as well as the “to and from” tasks that are outside the scope of the problem. The OV-5b can identify issues that were not clearly present in the OV-5a (functional decomposition) (DODCIO 2010).

The OV-5b for the employment of UAVs identified key resource inputs/outputs as well as maintenance and pre-flight tasks (Figure 14). The OV-5b was designed using the functional flow between deploy, launch, operate, and recover high-level functions. The deploy, launch, operate, and recover is a loop sequence that begins when a SAG is in position to launch communication UAVs and ends once the “over-the-horizon” communication mission is complete. The loop begins with conducting maintenance. A weather check uses weather data as an input following mission receipt. If the weather is bad, the UAV goes back to maintenance. If the weather is good, the launch and recovery systems can be set up. Next, the crew performs pre-flight checks on the UAV, launch, and recovery equipment. If any pre-flight check fails, the UAV and equipment go to maintenance. At the same time, intelligence provides updates on the threat, data relay, and team configuration information. Receipt of all necessary mission information prompts uplink to the UAV. Launch personnel position the UAV for launch and clear the airspace if all pre-flight checks are good and then they launch the UAV.

The UAV will determine its flight altitude and airspeed, as well as receive coordinate information in order to determine its current location and then move to a new waypoint based on the mission data upload. This process loops until the UAV is at its final destination. Once the UAV is at its final destination, it will determine loitering time based on remaining power information. If it has the required power, it will start its communication loop. This loop consists of the UAV receiving an incoming signal, processing the data, and then transmitting that data to a receiver. This loop continues until the power level reaches to the UAV’s minimum threshold value. Then, the crew confirms its suitability for recovery. The SAG tracks the UAV and deploys equipment to retrieve

the UAV. The UAV then enters maintenance and the loop begins again. Figure 14 shows the overall process while Figures 15–18 provide detail.

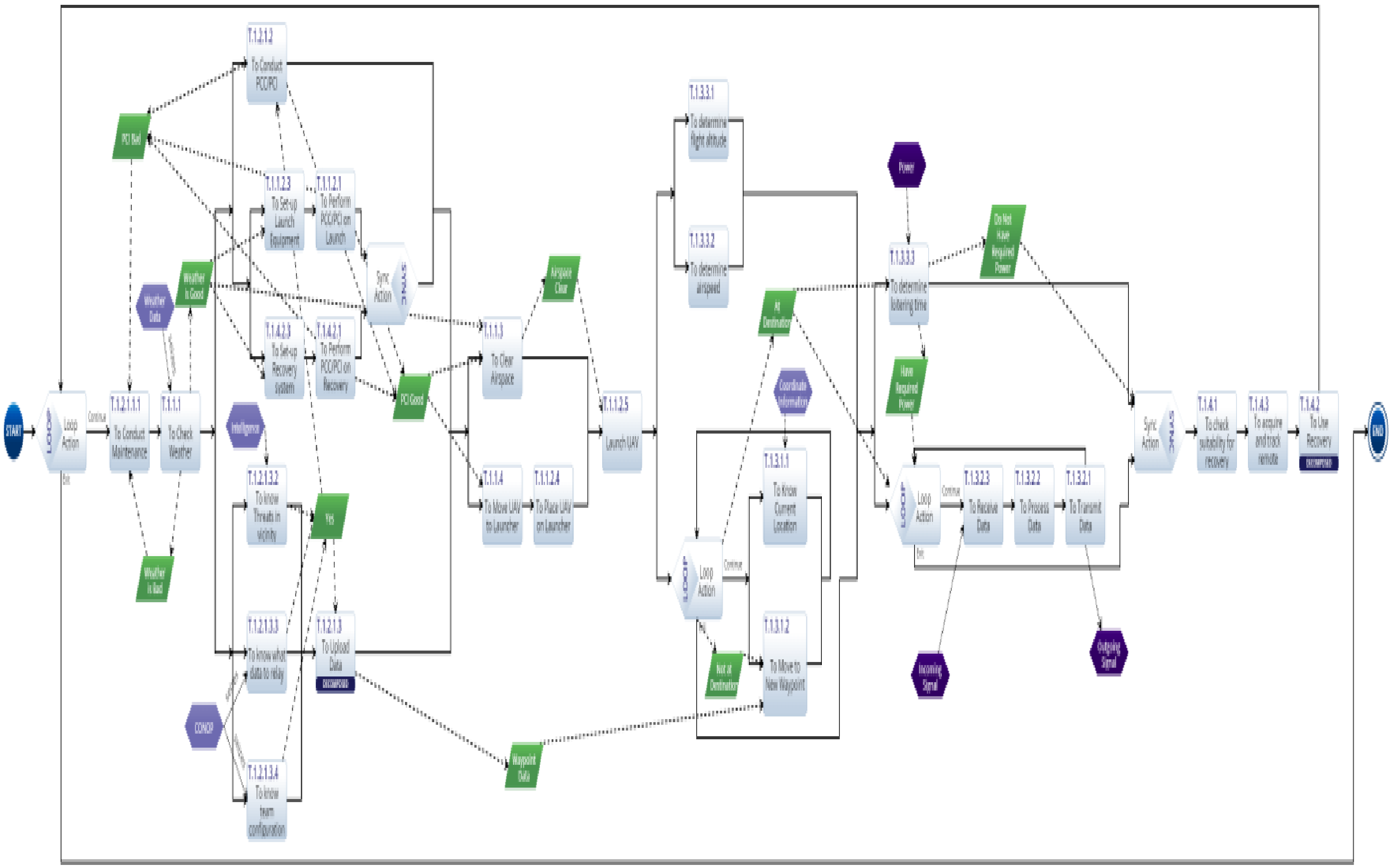


Figure 14. Overall View of Activity Model (OV-5b).

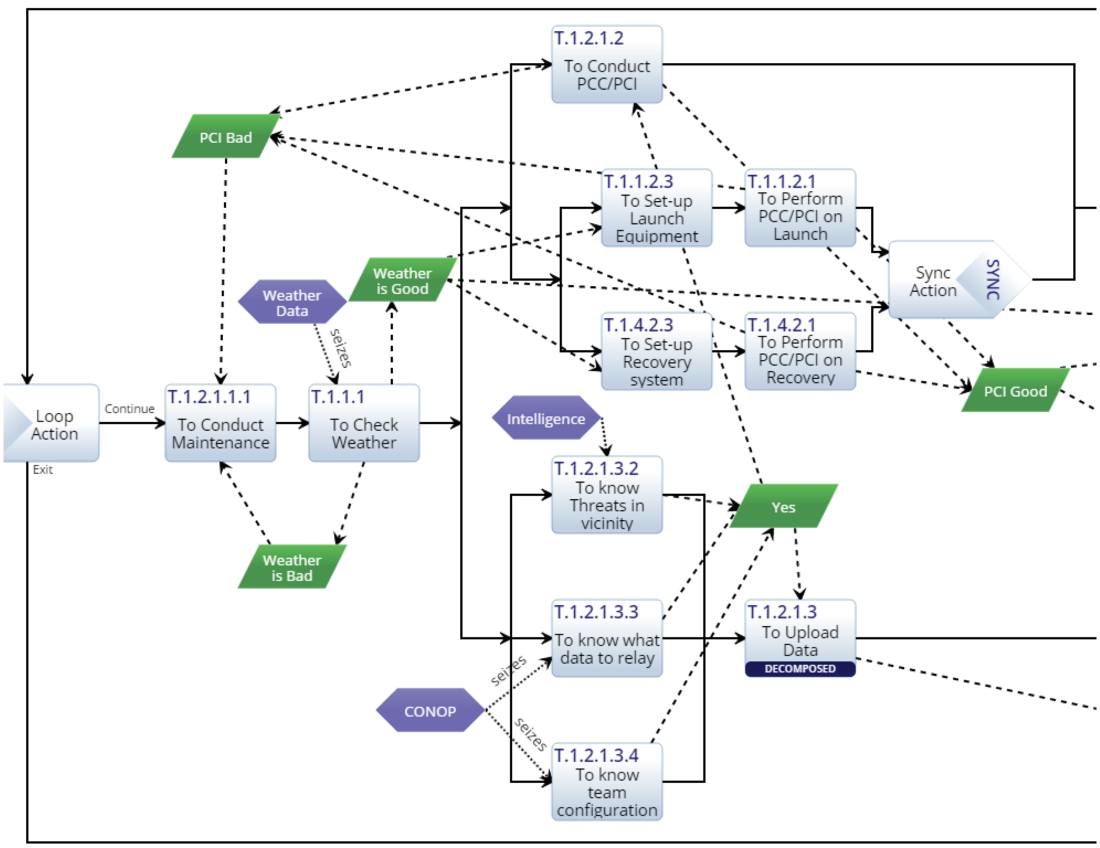


Figure 15. Deploy Sub-functions of the Activity Model (OV-5b).

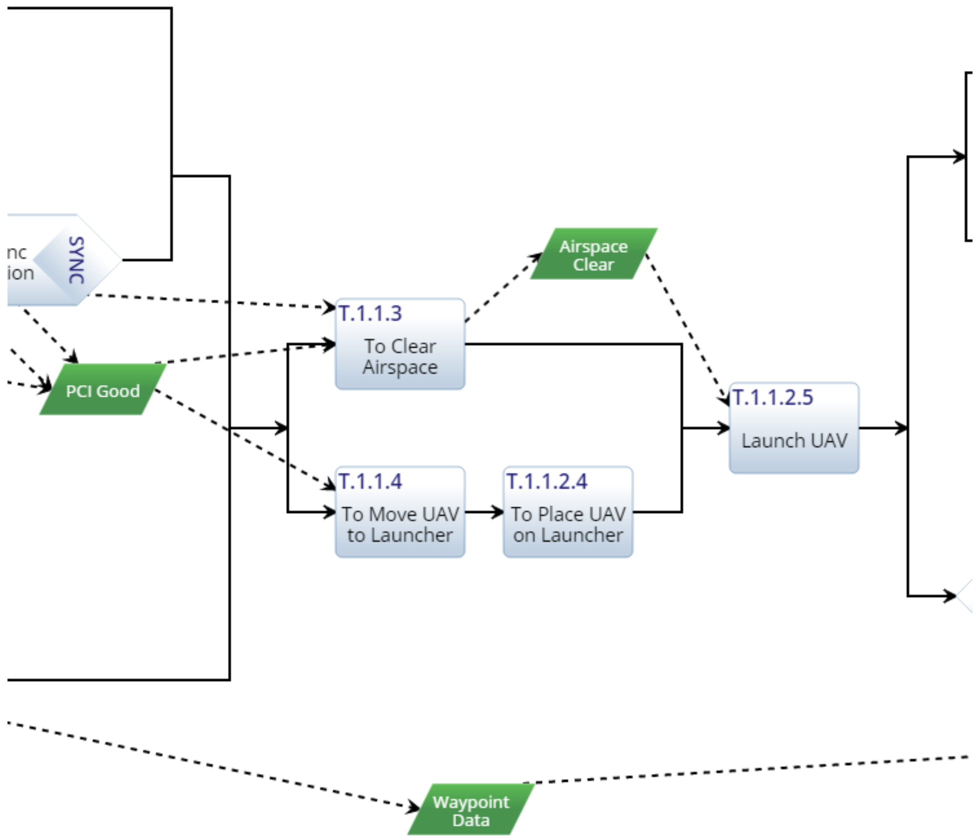


Figure 16. Launch Sub-functions of the Activity Model (OV-5b).

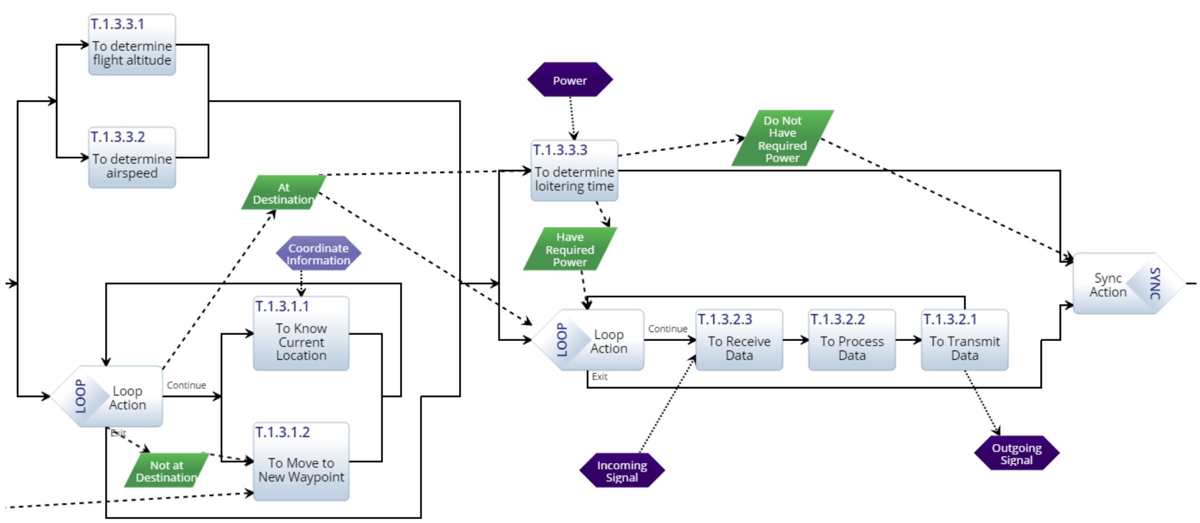


Figure 17. Operate Sub-functions of the Activity Model (OV-5b).

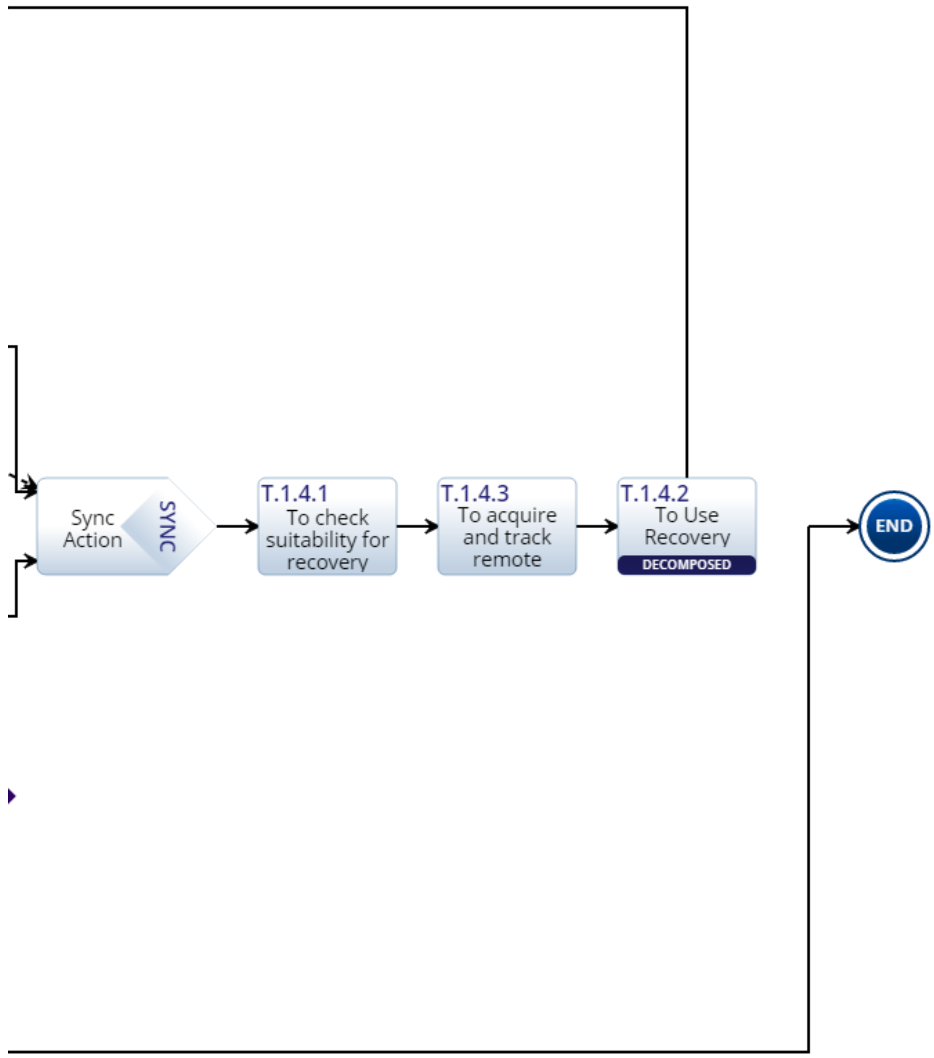


Figure 18. Recover Sub-functions of the Activity Model (OV-5b).

The OV-5b helped illustrate the deploy, launch, operate, and recover process that is required to complete the communication "Fire Web." The required information inputs/ outputs and decisions outlined the internal and external processes that must be considered for the communication "Fire Web." These internal and external processes and information needs helped in deriving the critical operational issues for the system of systems. The development of the OV-5b also made it easier to design models and simulations to verify the deploy, launch, operate, and recover process.

V. CONCEPT OF OPERATIONS

A realistic framework which to consider system attributes and requirements, to weigh against a real-world tangible challenge was needed to focus the open ended theoretical statements found in the original tasking letter. Using a narrative driven problem, SEA23 tempered the technical discussions with reality, inspiring the team to think practically when considering what technologies and potential solutions will be available for the solution space. The concept of operations process defines what, why, who, where, when, and how the system will be used. Blanchard and Fabrycky (2011) use the building of missions as a part of developing system operational requirements.

> Once the need and technical approach have been defined, it is necessary to translate this into some form of an "operational scenario," or a set of operational requirements. At this point, the following questions may be asked: *What are the anticipated types and quantities of equipment, software, personnel, facilities, information, and so on, required, and where are they to be located? How is the system to be utilized, and for how long? What is the anticipated environment at each operational site (user location)? What are the expected interoperability requirements (i.e., interfaces with other "operating" systems in the area)? How is the system to be supported, by whom, and for how long?* The answer to these and comparable questions leads to the definition of system operational requirements, the follow-on maintenance and support concept, and the identification of specific design-to criteria and related guidelines. (61, emphasis in original)

Building the scenario was not easy, but significant help came from the shared classes and workshops in which SEA23 participated. The team used a scenario similar to the OA4602 Joint Campaign Analysis and OA4604 Wargaming Applications courses, as well as the CRUSER Warfare Innovation Workshop. As the project progressed, so too did the scenario development to stay in line with the prescribed capability.

A. NARRATIVE

CAPT Kline developed the scenario presented during OA4602, OA4604, and the Warfare Innovation Workshop. "Maritime War of 2030" focuses primarily on Chinese and Russian expansionism in the first Pacific Island chain and in the Baltic Sea,

respectively (Kline 2015). SEA23 decided that it was a natural starting point and that it applies with minor modification. The problems presented by the contest in the littorals by regional hegemons fit well with the goals of integrating cross-domain naval fires using unmanned systems. In both the South China Sea and the Baltic Sea, the expectation is of a regional power creating an Anti-Access and Area Denial Environment. In a localized area, adversaries can challenge U.S. forces from accessing a designated international sea by use of long range, anti-ship missiles launched from land, surface ships, and submarines. The second half of the A2AD environment, area-denial, can be done through methods such as GPS denial. SEA23 focused on the China portion of the scenario to shape its study.

In 2030, China has overtaken the United States as the largest GDP in the world but is continuing to seek natural resources to expand its economic base at home. The political, fiscal, economic, and military expansions that China began in the early 2000s has continued and accelerated, in large part because of cooling tensions between mainland China and Taiwan that have led to stronger economic and social ties. By 2030, the two are essentially a singularly governed body. Taiwan has allowed China to build military installations on Taiwan to include high frequency surface wave radar systems and passive collection systems. Because of the increasingly closer ties between China and Taiwan, Taiwan has begun purchasing the bulk of its military goods from the People's Republic of China. This expansion onto Taiwan by the Chinese has allowed them increased ability to monitor and track naval surface traffic moving into the South China Sea from the East Philippine Sea.

Continuing the process begun in the 2010s, China has built multiple islands throughout the South China Sea. The militarization of the islands occurred rapidly with the addition of military airfields, as well as naval refueling and refitting capabilities. Additionally, multiple reef islands "have both surface to air installations (S-500) and anti-surface cruise missile mobile sites (advanced YJ-62s)" (Kline 2015). China has also threatened the invasion of Palawan, Philippines and Natuna Besar, Indonesia. Due to Natuna Besar's central location in the South China Sea, China can effectively monitor and track all surface vessel traffic moving through the South China Sea. With the man-

made islands and the possible invasions, China positioned itself to make good on their threats to prohibit international traffic through its claimed territorial waters encompassing the "Nine Dash Line" (Keck 2014) (Figure 19). China has warned that external interference in the territorial claims disputes will lead to open conflict, leaving open the possibility of nuclear escalation.

Figure 19. China's Nine Dash Line Claims in the South China Sea.
Source: Keck (2014).

The United States has continued to increase its ties with other partner nations in the region as part of the Pacific pivot begun during the Obama administration. Japan and the United States have strengthening social, economic, and military connections with additional littoral combat ships (LCS) home-ported in both Yokosuka and Sasebo to

supplement the carrier strike group (CSG) and expeditionary strike group (ESG) stationed in each respective location. United States forces have maintained their presence on the Korean peninsula; however, the warming of North and South Korea relations lessens the need for an extensive troop presence. Bordering the South China Sea, the Philippines continue to look to the U.S. to support their interests in the face of Chinese aggression. Along with Diego Garcia in the Indian Ocean, Subic Bay, Republic of the Philippines, is one of the U.S.'s primary logistics staging bases in the region. The re-opening of Clark Air Force Base provides U.S. forces with an expeditionary base in the area of responsibility. The city-state of Singapore has also allowed the enlargement of the U.S. presence on it. There is now a squadron of eight LCS homeported on the island as well as a squadron of P-8 maritime patrol aircraft. Additionally, the Marine Corps has expanded its presence in Darwin, Australia, to a battalion landing team (BLT). These regional allies have requested United Nations assistance in countering the Chinese threat, specifically from Japan and the United States. Because of the current Chinese military emplacements, U.S. forces must be able to maintain command and control linkages while operating with an offensive-mindset.

1. Understanding the Narrative

This narrative presents an operating environment drastically different from what many current active duty naval officers face. Since the fall of the Soviet Union in 1991, the United States has been the singular world power and has had no peer competitor. For the past 15 years, American forces have responded to an insurgent asymmetric threat, allowing regional powers an opportunity to gain a larger role in the world. China's strong historic and nationalist views have perpetuated the once third world nation into an economically vibrant country with the ability to support regional expansionism, with ever-increasing means of reaching out to the world. Though the two nations have strong economic ties, China and the United States do not agree on many foreign policy issues.

The South China Sea has many factors that make it especially vulnerable to conflict. First, throughout it are multiple resources rich areas. The region is "rich with fish and is believed to hold huge oil and gas reserves beneath the seabed" (McDowell

2011). Since there are at least seven nations that have competing claims to at least parts of the sea, the potential for conflict is high. There are also major commercial sea-lanes running through it from the Strait of Malacca and Strait of Singapore in the southern entrances to the Formosa and Luzon Straits in the north drawing outside attention. The area is no longer simply a regional squabble. Because China is the largest and most capable of the competing nations, most others look to the U.S. as a counterbalance. This is why China is actively pursuing means to prevent the U.S. Navy from operating freely throughout the South China Sea.

2. Tactical Situation

The current model for U.S. Navy surface operations centers on the aircraft carrier, a construct that has existed since the Second World War. Accompanying the carrier are a guided missile cruiser, at least one guided missile destroyer, and often a Military Sealift Command (MSC) supply ship. Since each carrier costs over $10 billion U.S. dollars and has over 5000 sailors stationed aboard, the loss of one of these vessels is unacceptable. China has the ability to track and target these large ships from hundreds of miles away using bases on their mainland, as well as from their smaller man-made islands. The basic building block of U.S. naval operations must change to counter the new threats. Additionally, the U.S.' reliance upon GPS is under threat because of the potential adversary's demonstrated ability to disable satellites and create a DDIL environment. The Navy must overcome the challenges presented by DDIL by being prepared to operate using the concept of graceful degradation. In a paper written for the 18th International Command and Control Research and Technology Symposium, Dr. Jonathan Czarnecki of the Naval War College and Colonel K. Todd Chamberlain of the Army Capabilities Integration Center describe graceful degradation as a complement of resilience, robustness, and redundancy.

> Graceful degradation, or fault tolerance in engineering terms, refers to the ability of systems to continue functioning, at least for a time, after critical processes or sub-systems are compromised or destroyed. One popular concept of recent times, resilience, attempts to capture the graceful degradation idea. However, resilience is insufficient to account for a system that has the quality of graceful degradation. Two other related

> concepts, robustness and redundancy, complement resilience. (Czarnecki and Chamberlain 2013)

Practically speaking, this means that sailors must be able to use a variety of different systems to operate their weapons systems using both organic and inorganic resources. This is a shift in tactical thinking. Sailors must return to solving problems as a relative movement between vessels, not with exact geo-locations from GPS. SEA23 took the concept of adaptive force packages to create tactical force structures, which aims to pair the right resources for the tasking at hand. Former NPS student Sean Bergesen explored this concept, then known as Adaptive Joint Force Packaging, in detail in his 1993 master's thesis.

> A new force planning and employment concept is now being developed which attempts to address some of the more difficult challenges presented by the post-Cold War security environment and attendant reductions to the U.S. military force structure. This concept, known as Adaptive Joint Force Packaging (AJFP), intends to address those challenges by "packaging" forces drawn from any or all of the individual Services into new, and in many cases, unconventional combinations. (Bergesen 1993)

The Naval Expeditionary Combat Command made this concept official doctrine in 2012 and the Navy Surface Forces command is conducting operational studies to build a similar doctrine. A SAG and an AFP are distinct entities. A SAG is comprised of cruisers, destroyers, and littoral combat ships or frigates with a specific mission while the AFP can be made of any number of different vessels to meet any potential mission. An AFP can consist of two "shooters," either destroyers or cruisers, and one slightly larger ship that will have a high capacity for carrying unmanned systems (UAVs or potentially USVs or UUVs). This provides offensive and communications capability for lethal fires without endangering the aircraft carrier. The AFP will carry a number of UAVs that will form a relay line-of-sight network that can stretch up to and beyond 500 nautical miles linking detection assets to the missile firing vessels. The assets that will be detecting the adversary will be manned and unmanned vehicles, autonomous vehicles, though this detection system is outside the SEA23 project's scope. For analytical purposes in providing a system lower bound for UAV capacity, SEA23 selected a three-DDG AFP to

support in this scenario. The team decided this based on which current Navy assets have the least amount of flight deck and hangar space available.

B. CRITICAL OPERATIONAL ISSUES, MEASURES OF EFFECTIVENESS, AND MEASURES OF PERFORMANCE

In the development of new military equipment, the Joint Capabilities Integration and Development System (JCIDS) require the explicit definition of what that item shall be able to do. The Key Performance Parameters (KPP) are the performance traits of the future system (DAU 2013). The team identified three types of KPPs. They are Critical Operational Issues (COI), Measures of Effectiveness (MOE), and Measures of Performance (MOP). COIs, MOEs, and MOPs are essential to the building of an effective Test and Evaluation Master Plan (TEMP). The Defense Acquisition University glossary defines them.

1. Critical Operational Issues (COI)

> COIs are key operational effectiveness or suitability issues that must be examined in operational test and evaluation to determine the system's capability to perform its mission. COIs must be relevant to the required capabilities and of key importance to the system being operationally effective, operationally suitable and survivable, and represent a significant risk if not satisfactorily resolved. A COI/COIC is normally phrased as a question that must be answered in the affirmative to properly evaluate operational effectiveness (e.g., "Will the system detect the threat in a combat environment at adequate range to allow successful engagement?") and operational suitability (e.g., "Will the system be safe to operate in a combat environment?). COIs/COICs are critical elements or operational mission objectives that must be examined, are related to Measures of Effectiveness (MOE) and Measures of Suitability (MOS), and are included in the Test and Evaluation Master Plan (TEMP). (DAU Glossary 2016)

2. Measures of Effectiveness (MOE)

> The data used to measure the military effect (mission accomplishment) that comes from using the system in its expected environment. That environment includes the system under test and all interrelated systems, that is, the planned or expected environment in terms of weapons, sensors, command and control, and platforms, as appropriate, needed to accomplish an end-to-end mission in combat. (DAU Glossary 2016)

3. Measures of Performance (MOP)

> System-particular performance parameters such as speed, payload, range, time-on-station, frequency, or other distinctly quantifiable performance features. Several MOPs may be related to the achievement of a particular Measure of Effectiveness (MOE). (DAU Glossary 2016)

The challenges of the A2AD and DDIL environment in the South China Sea guided development of critical operational issues, measures of effectiveness, measures of performance, and data requirements. For example, development of the COI1 “Will the system reliably and quickly relay target-quality data?” occurred with MOEs like “Minimize relay time within the node platform” and MOPs like “Time for input/output of relay signal shall be less than that of government off-the-shelf (GOTS) specifications” in mind. A data requirement is then to measure delay time for signal transfer. The complete list of COIs, MOEs, MOPs, and DRs is found in Appendix D.

VI. ANALYSIS OF ALTERNATIVES

A. GOAL

The SEA23's analysis of alternatives provides sponsors and stakeholders with a concise set of alternatives for networks and platforms. By modeling the system of system with various physical constraints, the number of platforms (nodes) required to cover an area can be determined using ExtendSim simulations. Selecting the 72-hour timeframe ensures the system is stressed during analysis. Currently, the carrier air wing (CVW) can provide approximately 17 hours of continuous coverage before requiring a break. If the system can work over a 72-hour period, it will not have issues working shorter periods. SEA23 assumes that the manned systems will not be productive in combat beyond that period based on current DDG manning.

The goal is to find the minimum number of nodes required for a 72-hour mission. SEA23 defines a node as each communications UAV used in the "Fire Web." The fewer nodes in the system, the more efficient it will be. This approach lowers the cost and reduces complexity; however, it leaves the system more susceptible to failures and hostile action. Additionally, not all networks will interact with other systems (such as ships and aircraft) in the same way. Some network types will require a more complex integration plan in order to communicate effectively. The project team will show various alternatives and recommended courses of action based on modeling and simulation.

B. APPROACH

From SEA23's discussions with sponsors and stakeholders, it was clear that an analysis of various platforms capable of carrying network equipment would be required. While the project focused on unmanned systems that comprise the larger systems-of-systems network, SEA23 could not disregard the network hardware (payload). A change in the payload will affect the requirements for the platform and a platform change can affect the payload it can carry. This caused some initial friction in the development of an analysis plan.

A plan was developed that can balance these competing interests. This required independent analysis of the various physical constraints and the limitations of the networks themselves. These were combined together to find the feasible number of nodes to constrain the simulation and provide realistic output. A summary of the analytical steps follows.

1. Perform Tactical Datalink (TDL) tradeoff analysis.
2. Match platforms to datalinks.
3. Determine minimum number of nodes.
4. Constrain with Horizon Limitations.
5. Constrain with Surface Action Group capacity limitations based on platform analysis.
6. Perform Reliability, Availability, and Maintainability simulation.

C. CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

For the purposes of this project, constraints were hard restrictions imposed by either institutional policies of the Naval Postgraduate School, the Systems Engineering and Analysis Department chair, or the sponsor, OPNAV N9I. SEA23 derived constraints from the tasking statement or from sponsor and department chair interviews summarized here:

- Study must remain unclassified due to foreign national involvement.
- Study must be completed on or before 17 June 2016.
- Study will focus on the platform architecture rather than the network architecture.
- Solution shall be feasible within the 2025–2030 timeframe.
- Solution shall be domain agnostic.

1. Limitations

Limitations are items left incomplete due to time constraints or classification issues. Several of these limitations resulted in an assumption. The limitations follow.

1. Precision Navigation and Timing (i.e., GPS) solutions overcoming the denied or degraded environment were not studied. Completion of the

study is not feasible in nine-months because of its complexity. See Assumptions 7–8.

2. Data classification levels prevented study of the undersea warfare domain. The addition of DARPA and other advanced projects into the scenario allowed the team to assume that they can handle the acoustic to radio frequency transition. See Assumptions 17–18.

3. The project was scoped to only look at the “to” section of Detect-to-Engage. Therefore, detection information, command and control and kinetic fires will be inputs and outputs to the studied system of systems.

4. SEA23 did not study the effects of cyber-attacks because of classification and time constraints.

2. Assumptions

SEA23 defined an assumption as a statement that is made and taken as fact solely for this study. Due to the project’s complexity and unclassified nature, it will be impossible to know every fact required to analyze alternatives and model the scenario. SEA23 researched the subsystem performance data at the open source level because of the international students on the team. The team consulted stakeholders when data was not available. Classified data required SEA23 to make assumptions based on experience. The goal was to create a working model that can be updated when better data was acquired achieving more accurate results. The project’s assumptions follow.

1. Timeframe is the year 2025–2030.
2. All platforms within the system of systems are identical.
3. Every node is a relay node (i.e., no sensors on board).
4. Three DDGs comprise the surface action group (SAG).
5. This SAG does not deploy the sensor nodes.
6. Satellite communications is not available.
7. GPS denied environment.
8. System can gracefully degrade from full GPS to no GPS capability due to a local relative navigation system being available.
9. Line-of-sight communications or data sharing is required.
10. Military assets are in an offensive posture.

11. Emissions Control (EMCON) restrictions are in place.

12. Vessels will be steaming in TACSIT-III, described as undetected and unlocated.by enemy vessels.

13. The SAG will be augmented by:

    - one or more submarines (SSN).
    - the Tactically Exploited Reconnaissance Nodes (TERN).
    - the Anti-submarine Warfare Continuous Trail Unmanned Vessel (ACTUV).
    - any other unmanned system that can carry the network
    - Note: This prevents further constraining of the problem. The system of systems can communicate with any platform carrying the network.

14. All DDGs in the SAG can carry Long Range Anti-ship Missile (LRASM).

15. LRASM has an unclassified range of 500 NM.

16. This scenario will only look at a maximum range shot (500NM).

17. SSN, ACTUV, and other external capable platforms can perform the acoustic-to-radio frequency links

18. Undersea assets must get signal to surface (in RF format) in order to communicate with the network.

19. Unmanned vehicles have an autonomous navigation capability.

20. All platforms are unmanned aerial vehicles (UAV).

    - SEA23 made this assumption because of current UAV capabilities to support cross-domain operations and because it allows for simpler logistics and maintenance efforts for the system.

21. All UAVs are co-altitude at 2000 feet.

D. TACTICAL DATALINK SELECTION

The U.S. military currently have multiple tactical datalinks (TDL) in operation. CAPT Good, surface warfare subject matter expert, briefed SEA23 on the complexity and cost of integrating a new system into existing AEGIS architecture. Because of this and

the timeline constraint, SEA23 preferred an existing network that meets the system requirements. If a new (or new to the Navy) network is chosen, the integration challenges will be significant and it is preferred that an existing pathway such as Link-16 or Cooperative Engagement Capability (CEC) be used. CAPT Good stated that it costs roughly $350 million to break into the AEGIS mainframe and run new code. It is significantly cheaper if our system can use Link-16 or CEC, or their pathways, into the AEGIS mainframe to reduce cost and complexity. The following systems are potential solutions:

- Link-16
- Cooperative Engagement Capability (CEC)
- Hawklink
- Multifunction Advanced Digital Datalink (MADL)
- Situational Awareness Datalink (SADL)
- "AV" Digital Datalink (DDL)
- "Elbit" Advanced Datalink (ADL)

Research indicated that the platform physical size and weight is critical to the analysis. SEA23 wanted to determine basic network characteristics to perform a link margin analysis to determine range requirements on the networks. The characteristics SEA23 needs for each datalink are its physical size, weight, power requirements, frequency bands, data rates, range, and integration requirements.

1. Link-16

Link-16 originated as the Tactical Digital Information Links (TADILs) with development beginning in the 1970s and IOC during the late 1980s. It is a widely used joint network installed on approximately 5000 platforms. The network operates on a timeslot architecture assigning participants a timeslot when the network "polls" them to push and receive their relevant data. The network can transmit either targeting information or voice ("J-voice") communications. It uses frequency hopping for security (Akers 2014).

Major advantages of this network are that it is an existing architecture and it is widely used by the Navy. However, Link-16 has lower data rates that can cause issues in anti-air warfare (AAW) where the speed of threats requires quick responses. The current system has, roughly, a 26.8-1102 kbps data rate, which is sufficient for anti-surface operations but not anti-air (ViaSat 2015a). A Link-16 module weighs approximately 50 lbs., can accept up to 350 Watts of power and operates in the 950–1250 MHz band. It has miniature forms and operates in the same band as the Tactical Air Navigation (TACAN) system. Its physical size can be as small as 7.62 x 7.5 x 13.5 inches (ViaSat 2015a).

2. Cooperative Engagement Capability (CEC)

Cooperative Engagement Capability (CEC) development began in the late 1980s with refinements continuing through the 1990s. Most U.S. Navy ships now have CEC capabilities and rely on its integration with the Carrier Air Wing's (CVW) E-2D Hawkeye. This system has a much higher data rate than Link-16, but comes at the cost of weight and size. Data rate numbers are classified, but estimates place CEC around 5 Mbps in the 4–8 GHz range (Moore et al. 2002). CEC has three major components: Data Distribution System, Cooperative Engagement Processor and Modified Weapons System (Figure 20).

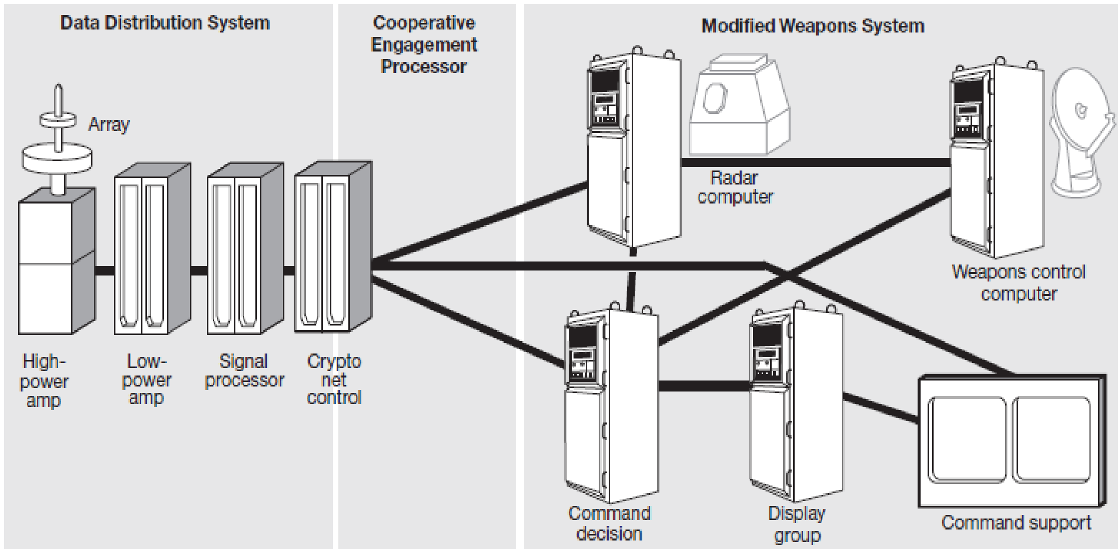


Figure 20. CEC Components. Source: Johns Hopkins (1995).

Since the system needs only to relay information, it will only need the CEC's Data Distribution System in order to function. Without a need to fuse sensor information or interpret the data in a relay node, significant weight reduction may be achievable. However, SEA23 was unable to find the current weight of the Data Distribution System. Therefore, an upper bound is the current airborne version of CEC onboard the E-2D. This is approximately 500 pounds and is approximately 2 x 2 x 3 feet (Johns Hopkins 1995).

3. Hawklink

Hawklink is a part of the Light Airborne Multi-Purpose System (LAMPS) linking U.S. Navy ships and MH-60 helicopters. Its specified range is up to 100 nautical miles, and it supports anti-submarine and anti-ship warfare. Because Hawklink only connects a single ship and helicopter, it is infeasible for this project (Janes 2016). It operates in the 14.5-15.4 GHz band with an approximate data rate of 45 Mbps. Hawklink modules weigh just over 100 pounds and are approximately 8 x 15 x 23 inches.

4. Multifunction Advanced Digital Datalink (MADL)

Northrop Grumman developed the Multifunction Advanced Digital Datalink (MADL) to complement the Fifth Generation F-35 Lightning as its advanced network. It

provides a CEC-like capability while maintaining low observability using messaging formats similar to Link-16. MADL can support up to 25 terminals in a network and operates in the K-band. Because of its relative newness, its performance characteristics remain classified rendering it unfeasible for inclusion in this project (Akers 2014). However, SEA23 recommends that future work in this area include MADL as a strong alternative for use in cross-domain data exchange.

5. Situational Awareness Datalink (SADL)

Currently in operation onboard the F-16 Fighting Falcon and the A-10 Warthog is the Situational Awareness Datalink (SADL). Further developments allow for integration with Link-16 networks for data reception. Its weight is approximately 150 pounds and it operates in the same frequencies as Link 16. It has an approximate size of 13 x 23 x 35 inches. However, it only has a data rate of about 256 kbps. The network is not a viable option due to low data rates and integration issues with Navy platforms (ViaSat 2015b).

6. Other Networks

SEA23 also looked at networks that are not currently U.S. military data links. Some are still in development resulting in fewer known specifics. After integration, they will not have any additional hardware because encryption, decryption, and language translation will only occur at the end users. This shows that lightweight networks can be useful in the project’s CONOPS with further development by 2025–2030. Choosing alternative networks creates integration issues outside the project’s scope. The architecture for integration will be relatively simple (Figure 21).

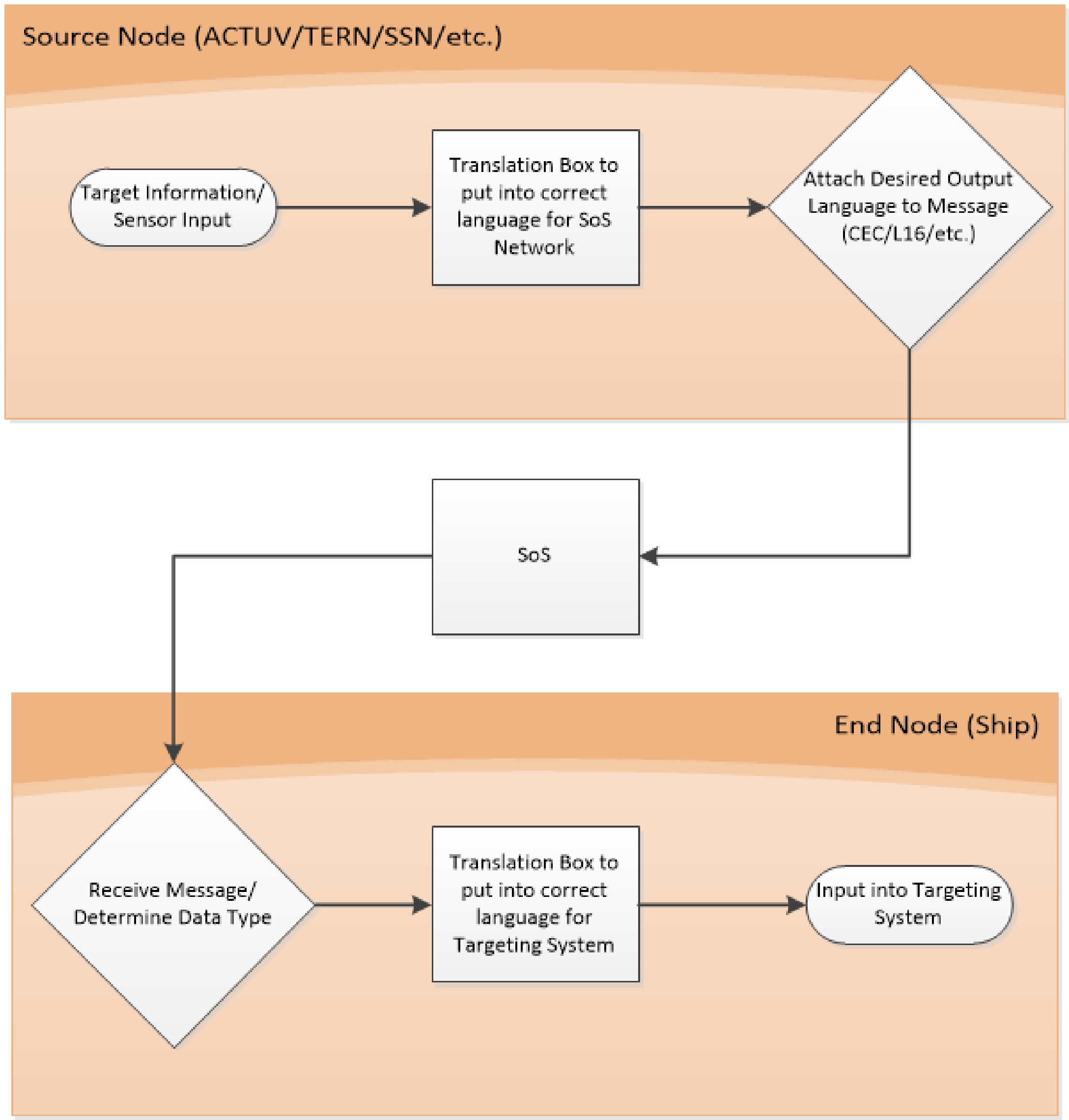


Figure 21. Possible Integration Architecture for “Other” Network.

As shown in Figure 21, only the end nodes that are outside the scope of this study will need to have additional hardware. The simplest way will be to make the data look as if it were Link-16 or CEC data so that a new pathway into the AEGIS mainframe will not be required. This is a very simplistic assessment and warrants further research but is beyond the scope of this study.

7. “AV” Digital Datalink (DDL)

The Aerovironment (AV) Digital Datalink (DDL) is a small, lightweight network that provides video capability to the network. It uses an Internet protocol (IP) based network to provide interoperability between nodes. This network will require massive integration to be used in this context but if done can prove to be very useful. It is approximately 2x5x0.5 inches in size and weighs only 0.22 pounds. It supports a data rate of about 4.5 Mbps (Aerovironment 2015).

8. “Elbit” Advanced Datalink (ADL)

The Elbit systems Advanced Datalink (ADL) is an Israeli system currently used only in land warfare. It operates in the 1400–1600 MHz range with an option to operate in the 400–6000 MHz range. It also allows for a 1–9 Mbps data rate and is approximate 5x4x3 inches in size with a weight of less than one pound. The system fits the scenario; however, there will be significant integration issues (Aerovironment 2015).

E. LINK MARGIN ANALYSIS

SEA23 granted further consideration to Link-16, CEC, and Other. The Other category represents a combination of DDL, ADL, and similar networks to ensure that all required data is available to execute a link margin analysis. This is to determine range more accurately using the project assumptions. The calculation does not take into account the horizon limitations as a function of antenna height. Table 8 shows all required factors in a link budget calculation.

Table 8. Link Budget Calculation. Adapted from Harney (2013).

Component Values and Requirements	
P_T	Transmitter Power
G_T	Transmit Antenna Gain
L_T	Transmit Loss
L_A	Atmospheric Loss (rain)
L_R	Receive Loss
G_R	Receive Antenna Gain
T	Antenna Temperature
B	Bandwidth
R	Range
F	Noise Figure
k	Boltzmann Constant
$16\pi^2$	Constant
λ	Wavelength (20 GHz)
CNR_R	Required CNR

SEA23 calculated the range of the communications system using an adaptation of Equation 2.10 from Volume Five of ***Combat Systems Engineering*** (Harney 2013).

$$R = \left[\frac{P_T G_T L_T L_A L_R G_R \lambda^2}{kTBF \cdot 16\pi^2 CNR_R} \right]^{1/2}$$

Table 9 displays the data used in the above equation to calculate theoretical ranges as a function of system power and specifications. Most of these parameters are the same across the range of platforms. The two that vary across platforms are the data links' bandwidth and wavelength.

Table 9. Input Variables for Three Tactical Datalinks.

Variable	Link-16	CEC	Other
P_T (Watts)	200	200	200
G_T	19.99	19.99	19.99
L_T	0.7	0.7	0.7
L_A	0.1	0.1	0.1
L_R	0.7	0.7	0.7
G_R	10	10	10
λ (meters)	0.2727	0.4997	0.138157
k (Joules/Kelvin)	3.18E-23	3.18E-23	3.18E-23
T (Kelvin)	500	500	500
B (Hertz)	4E+07	1E+09	1E+09
F	2	2	2
CNR_R	2	2	2

SEA23 chose 200 watts for the input power based upon the DOD's Policy and Procedures for Management and Use of the Electromagnetic Spectrum, which outlines Link-16 certification requirements (DODINST 4650.01 2005). 200 watts is a reasonable output power and it will be beneficial to compare the networks at the same ranges.

Transmitter antenna gain of 13 dBi is appropriate for the scenario's mesh geometry according to Cobham Antenna Systems (Cobham 2015). A transmission loss of approximately 0.7 is accurate due to cumulative design constraints. Atmospheric losses will be great in the South China Sea due to high humidity in the region and other obscurants (Harney 2013). Table 10 summarizes the theoretical ranges of the three systems.

Table 10. Results of Link Budget Calculations.

Tactical Datalink	**Theoretical Range (NM)**
Link-16	**325**
CEC	**119**
Others	**50**

F. TDL TRADEOFF ANALYSIS

Table 11 summarizes the tactical datalinks' physical characteristics.

Table 11. Summary of Trade-off Parameters for Tactical Datalinks.

Tradeoff for TDLs							
	Link-16	Cooperative Engagement Capability	Hawklink	Multifunction Advanced Digital Link	Situational Awareness Data Link	'AV' Digital Data Link	'Elbit' Advanced Data Link
		(CEC)		(MADL)	(SADL)	(DDL)	(ADL)
Physical Size	7.62 x 7.5 x 13.5 inches	24 x 24 x 36 inches	8 x 15 x 23 inches	Unknown	13 x 23 x 35 inches	9 x 6 x 2 inches	5 x 4 x 3 inches
Weight	50 lbs	500 lbs	113 lbs	Unknown	150 lbs	2 lbs	0.8 lbs
Power required	350W max	Unknown	Unknown	Unknown	652 W	18 W	12 W
Band	L Band	C Band	Ku band	K and Ka band	L Band	Unknown	VHF
	950-1250 MHz	4-8 GHz	12- 18 GHz	20-40 GHz	950-1250 MHz	Unknown	4 MHz
Data Rate	26.8 - 1102 kbps	5 Mbps	45 Mbps	Unknown	256 Kbps	4.5 Mbps	9 Mbps

Table 12 summarizes the relevant parameters including the ranges calculated from the link margin for the chosen three options.

Table 12. Summary of Trade-off Parameters for Three Chosen Tactical Datalinks.

Tradeoffs for Selected TDLs			
	Link-16	**Cooperative Engagement Capability (CEC)**	**Other**
Physical Size	**7.62 x 7.5 x 13.5 inches**	**24 x 24 x 36 inches**	**9 x 6 x 2 inches**
Weight	**50 lbs.**	**500 lbs.**	**0.2 – 2 lbs.**
Power assumed	**200 W**	**200 W**	**200 W**
Band	**L Band**	**C Band**	**Various**
	950-1250 MHz	**4-8 GHz**	**2-9 MHz**
Data Rate	**26.8 - 1102 kbps**	**5 Mbps**	**4.5 – 9 Mbps**
Range	**325 NM**	**119 NM**	**50 NM**

G. POWER REQUIREMENT WEIGHTS

SEA23 assumed that the tactical datalink would use a separate power supply system from the rest of the unmanned vehicle that adds weight to the payload requirements. The CONOPS calls for an individual UAV eight-hour mission time; therefore, a battery life providing 200 watts of power will be required to operate for at least eight hours. This means that there will be a 1600 watt-hour (W-h) requirement for the battery. Lithium-Ion batteries have the remarkable characteristic of high energy density. A Lithium-Sulphur-Dioxide battery can provide up to 100 W-h per lb. of energy density. This means that an estimated weight of the battery will be about 16 pounds and added to the weights in Table 13 (Pisacane 2005).

H. PLATFORM SELECTION

1. MQ-8B Fire Scout

The MQ-8B Fire Scout (Figure 22) is a rotary wing unmanned aerial vehicle that is currently operational. It is fully autonomous and does not require a pilot for launch and recovery. It also has very few requirements for host ships and personnel. Currently, its total endurance is approximately eight hours and has a range of approximately 596 NM. However, it can only carry 300 pounds of payload, which is too low to carry CEC. Additionally, this UAV is large, measuring approximately 24 x 6 x 10 feet. The analysis found the UAV too large, not meeting system operational requirements, but it is included in the analysis because of its operational status. A more capable version, the MQ-8C, is also in use, but it is much larger and marginally smaller than an MH-60 Seahawk (Northrup Grumman 2015).

Figure 22. Sailors Operating an MQ-8B Fire Scout On-board a Ship. Source: Northrup Grumman (2015).

2. DP-5X Wasp

Dragonfly Pictures, Incorporated (DPI) UAV Systems is developing the DP-5X Wasp (Figure 23). This system is a small rotary wing UAV. It can carry a 100-pound payload at 110 knots up to 15,000 feet. It is much smaller than the Fire Scout. While it cannot carry CEC, it can easily carry Link-16 and other lightweight networks. This system requires no launch or recovery equipment and is fully autonomous. Two people can deploy this system in 15 minutes or less depending on level of preparation. It is small enough to carry up to 15 per DDG hangar (DPI 2014a).

Figure 23. DP-5X Wasp in Flight. Source: DPI Systems (2014a).

3. DP-14 Hawk

Resembling a miniaturized Chinook helicopter, DPI UAV also produces the DP-14 Hawk (Figure 24). It has a large cargo capability and can currently carry a payload of 430 pounds. It is also fully autonomous and only takes one person to setup and deploy in about 15 minutes. Currently its endurance is only 2.4 hours at maximum payload; however, SEA23 expects that 10–15 years of research and development will increase its ability. Additionally, the company advertises that placing a “pusher prop” on it will increase range and payload. It is reasonable to assume that with technology increases on the range and payload capabilities, as well as the reduction in weight of CEC, that this system can carry a CEC Data Distribution System Node.

Figure 24. A Worker Installs Rotors on the DP-14 Hawk.
Source: DPI Systems (2014b).

VII. MODELING AND SIMULATION ANALYSIS

A. DETERMINE MINIMUM NUMBER OF NODES

1. Methodology

In determining the minimum number of nodes, SEA23 approached it as a fixed area problem. Figure 25 shows the geometry of the area of interest. The intent is to fill this area with UAVs so that a communication signal can reach from the far end back to the SAG. By filling the area with enough UAVs, there will be sufficient coverage for the entire area so that no dead zones occur anywhere within this half-circle. The team desired that these UAVs be evenly spaced and always within range of another UAV so that no signal can be lost. SEA23 will show all attempted methods in the order they occurred, even failed attempts, to illustrate the process that the team undertook.

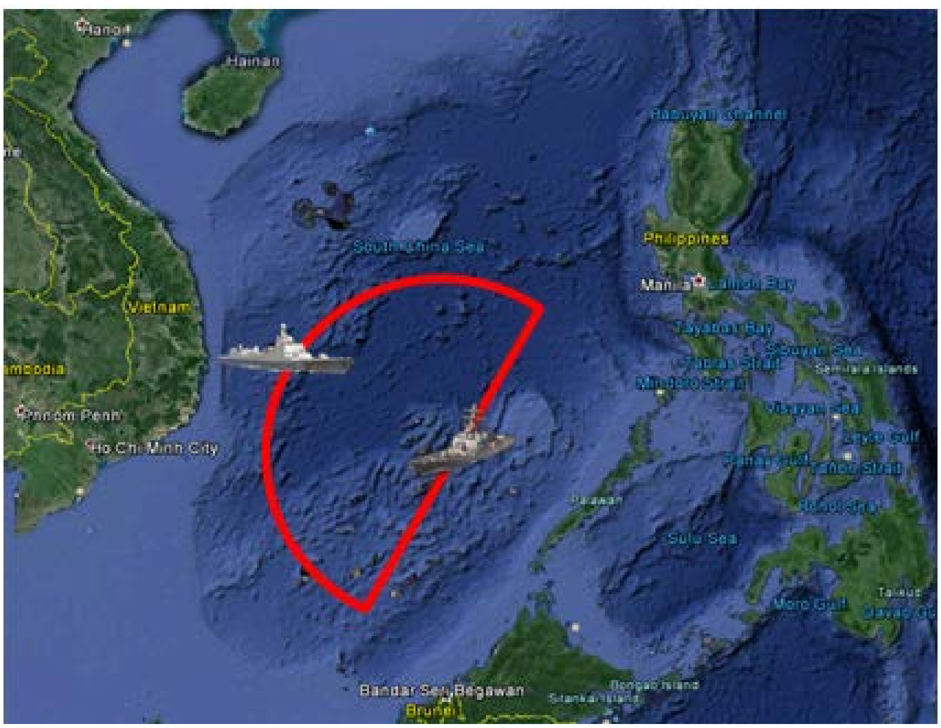


Figure 25. Geometry of Area of Interest.

Given the fixed area, increasing the number of nodes will decrease range between nodes. Originally, SEA23 attempted to determine what range should be between the nodes given a fixed number of nodes, but the team found this to be the incorrect way to look at the problem. The better question to ask was given a certain maximum communication range of a node, how many will be required to fill the space? Because of the change in thinking, SEA23 discarded the previously produced General Algebraic Modeling System and Java models. That process did develop estimated requirements so that work can proceed for the simulation. An area-packing problem determined the minimum number of nodes.

2. Horizon Limitations

A major physical constraint of communications is the curvature of the earth. At the frequencies our networks operate in, there is very little refraction or bouncing that occurs that allows other types of frequencies (e.g., HF) to travel great distances. The assumption for this study is that if there is not line-of-sight communications, then the system cannot communicate with anything. The following equation shows the relationship between the distance of the transmission (L_{TOTAL}) and the height of the transmitter (H_T) and receiver (H_R). (Harney 2013)

$$L_{TOTAL} = L_T + L_R = A\left(H_T^{1/2} + H_R^{1/2}\right)$$

The term (*A*) is a constant. In this case, it is 1.229 for (H) to be in feet and the output will be in Nautical Miles. The maximum range equation simplifies because the UAVs are co-altitude.

$$L_{TOTAL} = 2AH^{1/2}$$

Figure 26 shows the relationship between altitude and maximum range.

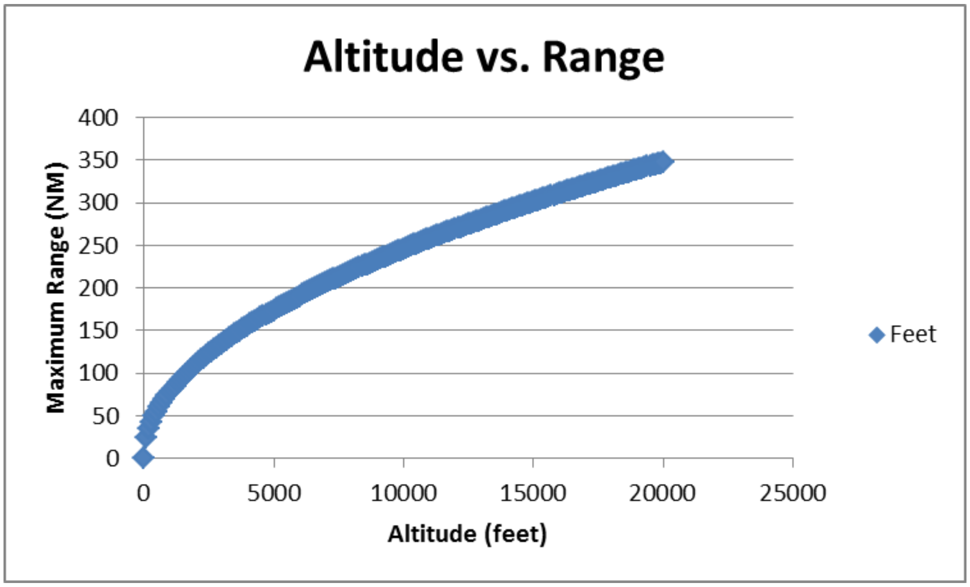


Figure 26. Relationship of Altitude (feet) to Maximum Range (nautical miles) Assuming Co-altitude UAVs.

The team made the initial assumption that all UAVs were co-altitude at 2000 feet. At this altitude, the maximum range for transmission is 110 nautical miles. This assumption enables a great range but also keeps the UAV low enough so that a surface platform will have to be within 55NM of the node to detect its transmission. However, after our initial runs of the model, the team determined that the number of nodes required at 2000 feet would be infeasible to operate. Therefore, the team looked at 5000 and 10000 feet to analyze how many nodes will be required.

3. General Algebraic Modeling System Methodology

SEA23 first attempted to use the GAMS software that can compute linear, nonlinear, and mixed integer optimization problems (GAMS 2016). SEA23 first tried to approach this question using linear programming, but encountered two problems:

1. Distance is not a linear function of placement, but a square root of squared numbers. Using Manhattan distances instead of Euclidean distances solves this problem. That will make it linear, and will throw us off by a factor of roughly 1.5 (Manhattan distance is always greater than Euclidean, so that will give us an upper bound).

2. The objective function considered the closest UAV to a given UAV. SEA23 numbered the UAVs from one to N. UAV number one was required to be within range of the SAG and each additional UAV had to be within range of at least one other UAV in the network. The minimum function is non-linear, and actually, not even convex, which will later cause modelling issues.

SEA23 attempted to use nonlinear programming methods, but this meant that a global optimal solution might not be found or exist. The minimum function problem was still present, so the team used nonlinear programming with discontinuous derivatives. This method is discouraged, but it was tested. As expected, this method generated poor results, especially when trying to solve for a large number of UAVs. SEA23 needed a different approach.

4. Java Model

Java is a well-known computer programming language. Programming in Java provided some flexibility in building the model to the desired specifications. Evolutionary algorithms are good for giving a good solution, but possibly not the optimal solution (Ragsdale 2012). SEA23's basic idea for an evolutionary algorithm is to:

1. Create an initial population of random optional solutions, called the first generation. The team placed the UAVs randomly. Optional solutions are chromosomes.

2. Rank the chromosomes. In this case, the rank is inverse to the maximum of all minimum ranges. The team must find the minimum for each UAV (required transmission range). SEA23 then selected the maximum, which is the transmission rate needed for this solution to work, as the number the program will attempt to minimize. This minimization will essentially find the most isolated UAV. In other words, the UAV that will have to transmit the furthest distance. A mathematical formula of this problem is given in the following equation:

$$
\begin{aligned}
&\max(\min \text{distance}(a, b)) \\
&\forall\, a \in \text{UAVs} \\
&\forall\, b \in \text{UAVs} \\
&\#b < \#a
\end{aligned}
$$

3. Creation of a new generation occurs after ranking the chromosomes. Each generation consists of 1000 chromosomes with each chromosome representing a possible solution. New generation creation occurs by taking

the best of the last generation, some of them as is, some of them with "breeding," i.e., taking two chromosomes, and creating a new one that is a mix of the two. This mixture was half of the UAVs from one solution and half from another. The other solution was a random choice from all other chromosomes in that generation. Breeding came by pairing UAVs from the two chromosomes, and the new one has a UAV in the middle between each pair.

4. After "breeding," random mutations to some of the chromosomes was done by picking a UAV in the chromosome, and placing it randomly somewhere else.

5. The program continues creating generations, up to a predetermined number, in this case, 10000.

There are problems with evolutionary algorithms. Primarily they are difficult to predict because of their embedded randomness. Because of this, SEA23 ran the program for a range of 1–50 UAVs, which resulted in a relatively smooth line, but with a few unexplained "bumps." There are also parameters to decide on when using evolutionary algorithms, such as number of chromosomes in a generation, number of generations, "breeding" method and "mutation" method, and the fact that they are hard to predict makes it very hard to find the "right" parameters. This is a trial and error process and it is difficult to identify the soundness of an answer. Finally, evolutionary algorithms may take a long time to run. This program took 24 hours to run for 1–50 UAVs. The program achieved a relatively smooth curve to show a relationship of the range between nodes as the number of nodes increased. Figure 27 shows the relationship achieved with the Java model. The y-axis shows the range between nodes in nautical miles. Given a fixed area, the insertion of more UAV nodes means that the range between them will decrease. This is important in SEA23's analysis because it shows whether there are sufficient nodes to support a specific communications network based on its range.

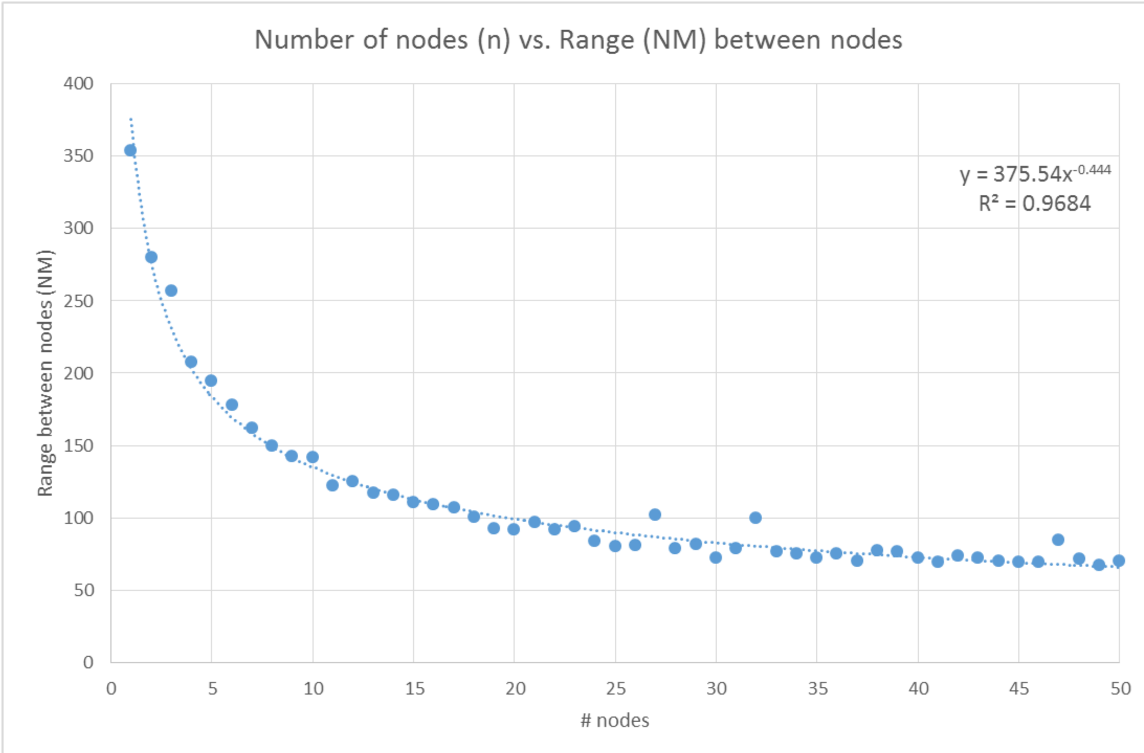


Figure 27. Range between Nodes as a Relationship to the Number of Nodes in a Fixed Area.

The curve is relatively smooth, but does have outliers because of the stochastic process of the evolutionary algorithm. A power curve fit the data well. Due to this essentially being a trigonometry problem, the team expected that it would be roughly a $-\sqrt{x}$ function. The curve fit has a power of (-0.444), which is close to (-0.5). This data provided an initial estimate to begin later simulations. Additionally, while the geometry may be tough, the team anticipated attainment of a smooth curve. SEA23 decided that we asked the wrong question. Following feedback from the second IPR, the team decided that this was an overly complex method to determining the number of nodes required. A better way was to approach this as an area-packing problem instead of stochastically placing the nodes. Given that one of our assumptions is that the nodes are evenly distributed, this made more sense and provided a set number of nodes required based on range of the communications system and altitude.

5. Area Packing Problem

SEA23 decided to re-approach the problem from a perspective of an area-packing problem based on feedback from the second progress review. Using a search theory scheme outlined in Professor Harney's 2013 ***Combat Systems Engineering***, there are two methods of packing circles: hexagonal and square. Each node can represent a circular search pattern since the antennas are omnidirectional. Figure 28 shows both hexagonal and square tiling.

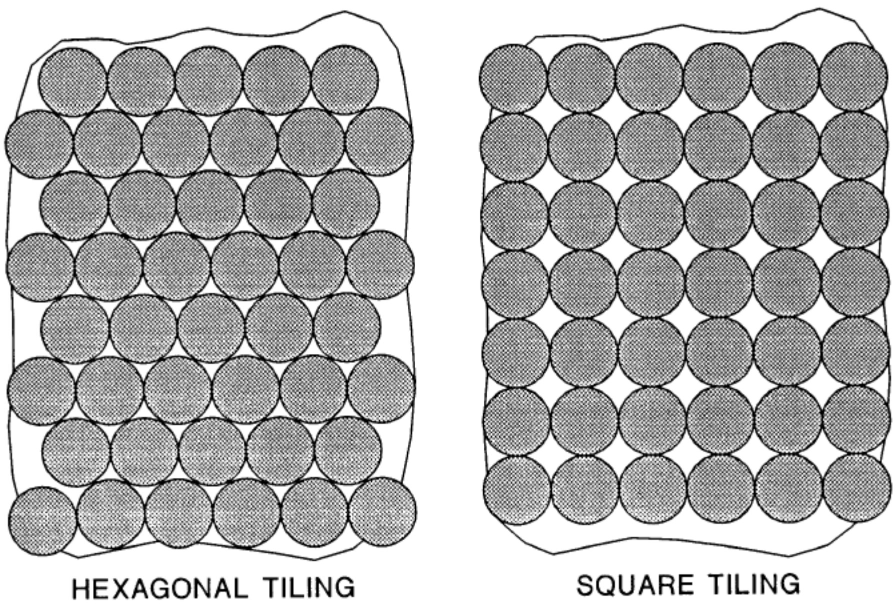


Figure 28. Hexagonal and Square Tiling (Packing) Patterns. Source: Harney (2013).

A cursory glance shows that hexagonal tiling offers the least amount of "white space" that is the area not covered. Because this is not a search problem, these nodes will be static for the purposes of the model. Therefore, there must be overlap so that the "white space" is nonexistent in order to ensure that the network can communicate 100 percent of the time. While it is a geometry problem to determine the amount of overlap required to rid the area of uncovered space, it involves calculating several different geometries and subtracting to find the leftover space. Figure 29 shows this problem's geometry.

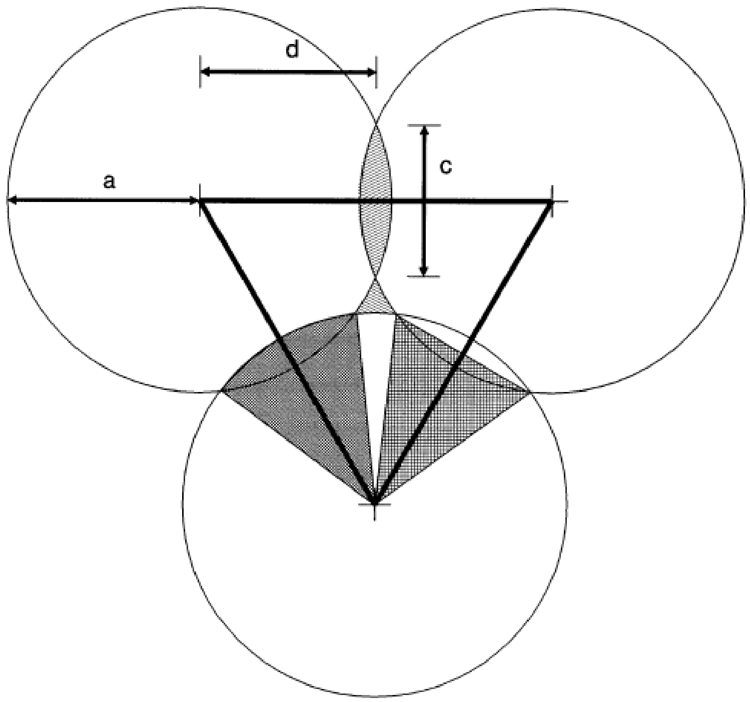


Figure 29. Geometry of Circular Overlap Problem. Source: Harney (2013).

In Figure 29, (a) is the radius of the circle and (2d) will represent the distance between the circles. For this study, (2d), the radius of the circle, represents the maximum range of the communications system and the distance between nodes. The parameter that the team is interested in is what the distance between nodes needs to be in relation to the max range of the node. Harney (2013) defines this overlap parameter as $\xi = d / a$. Through this relationship, the team determines how far apart the nodes can be for each network and how many will fill the area of operations. Consulting Figure 30 shows what this parameter needs to be in order to have complete overlap.

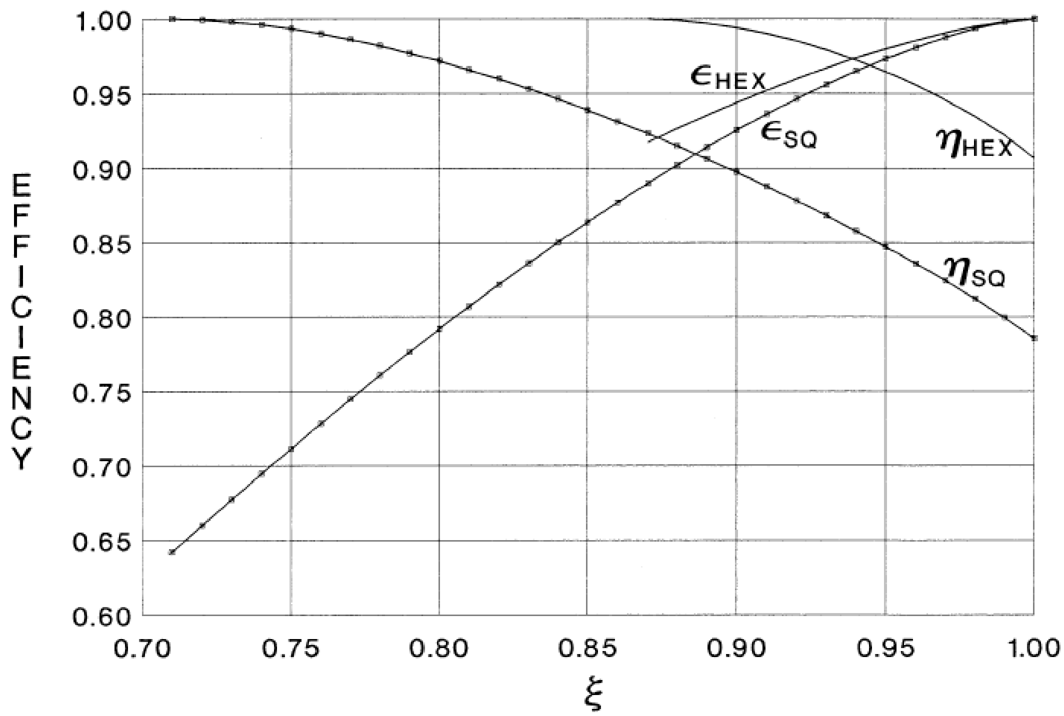


Figure 30. Relationship of Overlap Parameter (ξ) to the Fractional Coverage (η) and Coverage Efficiency (ε). Source: Harney (2013).

Using Figure 30, it is determined that the fractional coverage is 1.00 with an overlap parameter of approximately 0.86. To determine the number of nodes required, the range of the communications node must be multiplied by 0.86. The area of operation is a half-circle with a radius of 500 nautical miles. The area of this shape is 392,699 square nautical miles. By dividing the total coverage area by the area covered by a single node, the total number of nodes required is determined. The area of a single node depends upon its maximum transmission range and is simply the area of a circle:

$$\pi r^2$$

where (r) is the radius, or maximum transmission range of the individual node. Figure 31 shows the results of these calculations.

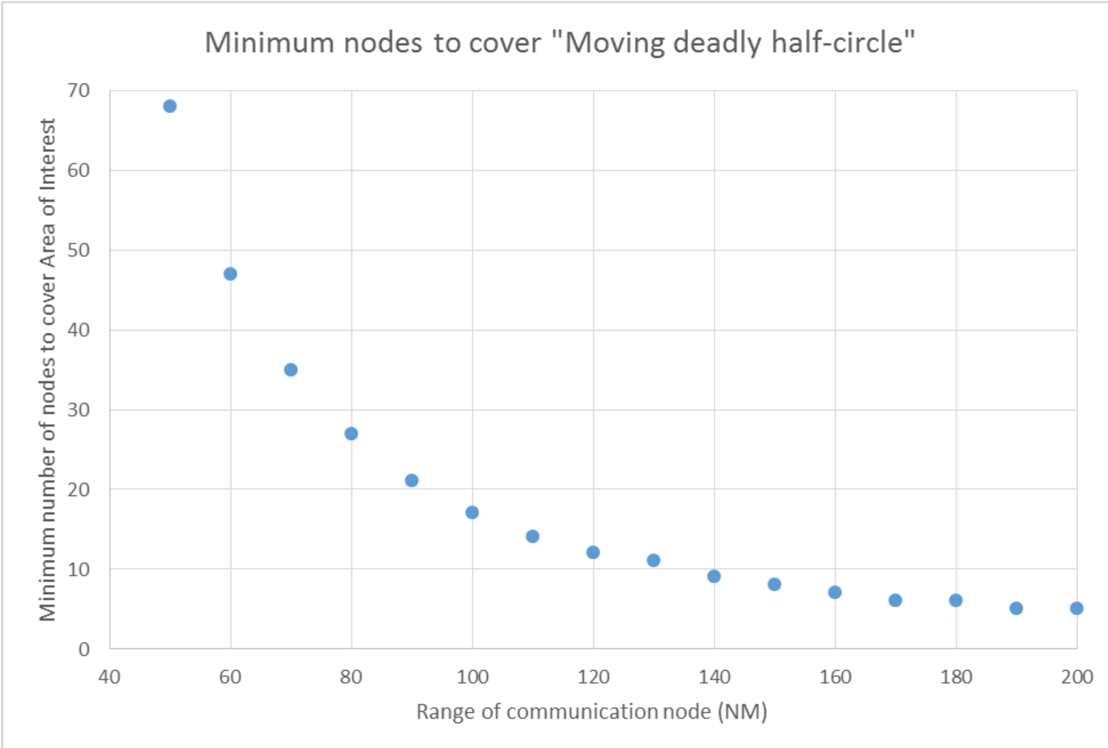


Figure 31. Minimum Number of Nodes Required to Cover Area Given the Range of the Communications Node. Note: X-Axis Does Not Start at Zero.

The team discovered an error after running several trial models that drastically changed the project team's calculations for the minimum number of nodes required. The project team had thought of these nodes as sensor nodes as in search theory instead of communications nodes. In a searching problem, too much overlap results in wasted coverage and time that assets could be looking for their target. However, this is a communications problem and overlap is required. This error led to an under-calculation of the minimum number of nodes required to fill the area. The communications signal must be able to reach another node. Therefore, the nodes can only be as far apart as their maximum range. From Figure 29, the parameter (d) must be equal to zero. The project team had incorrectly utilized the radius of the maximum range of a single node as the maximum distance between nodes. This means that there will be much more overlap than 0.86. The overlap must cover the next node as shown in Figure 32.

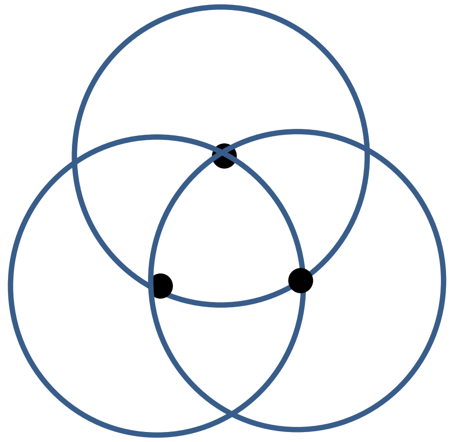


Figure 32. Diagram Showing Required Overlap of Nodal Coverage to Complete Network.

To model this overlap, the team performed another hexagonal area-packing problem. However, this time the team utilized half of the maximum range for a given TDL and assumed zero overlap. Since the nodes are communications nodes only and not searching for a target, overlap is not required. It is just required that the circles touch so that each circle modeled covers half the distance to the next node. Figure 33 shows how the models circles work in comparison to the physical range of the nodes.

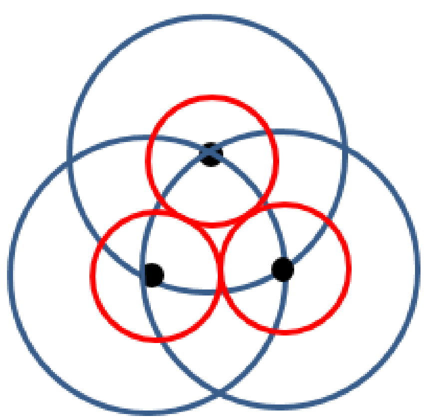


Figure 33. Comparison of Real Node Distance (Blue Circles) to Modelled Circles (Red Circles) for Area Packing Problem.

Since there is no overlap in this updated packing model, the team needed to figure out what was the total area to cover. For hexagonal packing with zero overlap, the area covered is equal to 0.9069 of the total area. (Eagle 2013) Since the total area is 392, 699 NM^2, the area required to cover is:

$$392699\ NM^2 \bullet 0.9069 = 356139\ NM^2$$

SEA23 found the number of nodes by dividing the area required to cover by the area of a single node. Table 13 shows the results of the required number of nodes for each TDL considered. Additionally, both CEC and the Other network category reach their power limits at or prior to their horizon limits. Therefore, only Link-16 will show a benefit to increasing altitude as discussed earlier.

Table 13. Number of Nodes Required at Various Altitudes for TDLs Considered

	Nodes Required		
Altitude (feet)	Link-16	CEC	Other
2000	38	38	182
5000	16	38	182
10000	8	38	182
Limitation	Horizon	Horizon/Power	Power

B. SAG CAPACITY LIMITATIONS USING PLATFORM ANALYSIS

The final physical constraint that the project team considered was how many UxV platforms can fit onto a SAG. The team considered an Arleigh Burke Class destroyer (DDG). This ship has two hangars and currently carries an MH-60 Seahawk in each one. The project team wanted to know how many of these UAVs could fit into the space of one helicopter. The MH-60's folded length, width, and height are approximately 41 x 11 x 13 feet. None of the UAVs considered are taller than 13 feet. The team only concerned the 41 x 11 feet of horizontal deck space and disregarded stacking for practical purposes (Lockheed 2001).

This is a much simpler packing problem than figuring out how many nodes can fit into the area because there is no overlap. The only necessity was to determine the two-dimensional size of each UAV and divide the total area of the MH-60 by the area of that UAV. After finding the maximum number for each hangar, it is simple to determine how many can fit in a SAG. The team wanted to keep an MH-60 on each DDG (in order to fulfill other mission roles that the UAV was not suited for), but not all combinations may allow that. Where possible, the team used only one hangar for the UAVs on each DDG in order to keep the manned helicopter asset available. Additionally, based on the reliability, availability, and maintainability simulation, the number of required nodes to keep the number of functioning nodes above the minimum number may necessitate giving up the manned helicopter to provide room for the UAV. Table 15 shows these UAV capacity analysis results.

C. RESULTS OF PHYSICAL CONSTRAINTS

After applying the various physical constraints, Table 14 shows the results of applying the physical constraints to the selected UAVs and TDLs.

Table 14. Matrix of Tactical Datalinks and UAVs with Associated Physical Constraints.

	L16	CEC		OTHER	
Payload Weight (lbs.)	66	516	516	18	18
Smallest Type of UAV	DP-5X Wasp	DP-14 Hawk	MQ-8B Fire Scout	DP-5X Wasp	DP-5X Wasp (no helicopters)
Max Payload (lbs.)	100	430	300	100	100
Range (Power) (NM)	325	119	119	50	50
Altitude (ft.)	2000	2000	2000	2000	2000
R (Horizon) (NM)	110	110	110	110	110
Max Distance between nodes (NM)	110	110	110	50	50
Minimum number of nodes	42	42	42	200	200
Length (ft.)	11.4	13.5	23.95	11.4	11.4
Width (ft.)	2.5	2	6.2	2.5	2.5
Area (ft^2)	28.5	27	148.49	28.5	28.5
DDG Capacity (single hanger)	15	16	3	15	15
SAG Capacity	45	48	9	45	90

The biggest takeaway from this table is that CEC currently does not have a platform that fully meets the requirement of being able to carry it. However, the DP-14 Hawk is close and developments may enable it to increase its payload over the next 10–15 years prompting further inclusion. Additionally, the 10–15 year time span may allow the physical lightening of CEC. However, the MQ-8B Fire Scout is not close to meeting requirements and too few platforms will fit in the SAG to accomplish the mission based on its size. The DP-5X Wasp can accomplish the mission and each DDG hangar is capable of holding 15 UAVs. The team dismissed “Other Networks” since it does not meet the required number of nodes. The maximum range of a UAV is affected both by the power output of the node and the horizon limitations as a function of altitude, summarized in the equation:

$$Max\,Range = Minimum\left[Range(Power), Range(Altitude)\right]$$

For both Link-16 and CEC, the SAG barely meets the required nodes before accounting for mission life cycle, reliability, availability, and maintainability. However, the minimum number of nodes represents the absolute minimum to keep the network 100 percent functional. After studying the data in Table 15, the team determined that Link-16 was the only viable candidate to continue studying. CEC will be incapable since its maximum transmission range is 119 NM. While an increase in platform altitude will decrease the minimum number of nodes required, CEC is already at its maximum range at 2000 feet. Any altitude increase will have negligible effects since it only has nine more miles of range than allowed at that altitude. Therefore, the team will study Link 16 further through an ExtendSim model at 5000 and 10000 feet. Table 15 shows Link-16 with its associated minimum number of nodes required at 2000, 5000, and 10000 feet.

Table 15. Link-16 minimum number of nodes required at given altitudes.

Altitude (ft)	2000	5000	10000
Min Nodes Required	42	17	9

D. RELIABILITY, AVAILABILITY, AND MAINTAINABILITY SIMULATION

Reliability, Availability, and Maintainability (RAM) are essential elements of mission capability. The reliability of the system is the probability that the system will perform under specified conditions for a given period. Availability of the system is a function of the frequency of failure, frequency maintenance activities, and the time it takes to complete the maintenance activities. System maintainability is its restorative ability, through maintenance actions, to a reach desired operational capability (DODINST 4650.1 2005, 1-1).

Reliability is important for the “Fire Web” system because the probability that a UAV will fail while in operation effects the system’s capability to perform its primary function of communicating and transmitting targeting data. Its simulation determines the effects a UAV failure will have on system performance. The availability of UAVs to

create the "Fire Web" system is important in ensuring the minimum numbers of required nodes to create the network are operating when needed. A simulation will assist in analyzing how the maximum UAV carrying capacity within a SAG effects the system's ability to meet performance requirements. The maintainability of the UAVs directly affects the time it takes to relaunch a UAV. Maintenance actions can be built into a model and simulated to determine the effect that maintenance actions have on the UAVs operational availability to complete the "Fire Web" network.

1. ExtendSim

ExtendSim is a modeling and simulation software package by *Imagine That!*. It is used as a design tool to predict the performance of potential new systems (Imagine That! 2016). SEA23 chose ExtendSim to model the availability of the "Fire Web" communications node system because it was a familiar tool taught and utilized in SE3250 Capability Engineering. It also provided an easy interface to integrate the system OV-5b (Figure 14) into an accurate modeling and simulation program.

The OV-5b was used to create the model because it specifically details the deploy, launch, operate, and recover cycle each UAV will be going through. The OV-5b identified critical inputs and outputs that were necessary for analyzing the results of the simulation. It facilitated the design of the reliability, availability, and maintainability model by illustrating the steps for each portion of the cycle. The OV-5b also helped with the evaluation of the approximate times each step will take because it used the lowest level functions. The OV-5b also illustrated the required input/output data needs for the system allowing identification of the critical information (capabilities) that the model will need to create an accurate prediction of system availability performance.

2. Assumptions

Assumptions were required for the system model because of either a lack of information or a classification barrier regarding different components, systems, or processes. We considered only UAV failures. We do not consider failure of equipment onboard the UAVs. We assumed that UAV failures only affect the time for maintenance

and repair once it returns to the ship; it does not affect flight time or time on station. The first assumption made for the model was the square footage of a DDG's hanger. SEA23 assumed that each DDG could fit one MH-60R Seahawk helicopter, its associated support equipment and personnel in one hanger bay (Lockheed Martin 2016). Therefore, the team determined the available footprint for the UAVs using an MH-60R's footprint (including support equipment and personnel).

SEA23 made many assumptions about UAV maintainability because of that information's non-availability to the team. First, the team assumed that all maintenance actions and repair parts were organic to the SAG. This creates no delay in receiving parts from outside the SAG; in other words the logistics delay time (LDT) is essentially zero. Reduction of administrative delay time (ADT) occurs because only the maintenance personnel chain of command is involved in paperwork. Group operational experience and the SWARM analysis conducted for SE3302 System Suitability, was used in developing maintenance action times (Hanna 2015). SEA23 assumed that minimum maintenance actions are refueling and system check, taking only five minutes (refuel and system check occurring simultaneously) based on information provided by the manufacturer (DPI 2016b). An average maintenance action will be refuel, system check, and replacement of a modular part, taking 15 minutes (refuel system and system check taking five minutes, replacement of part ten minutes). A long maintenance action will include refuel, system check, and repairs to fix a component, taking 360 minutes (refuel and system check taking five minutes, and component repairs taking the remaining time).

It was assumed that the UAVs, regardless of system type, will be capable of operating (total flight time from launch to recovery) eight hours and the SAG will be conducting a 72-hour operation. The UAVs will also be capable of carrying their specified TDL equipment. The team assumed that the maximum payloads for the UAVs would increase in the 10–15 year timeframe discussed in the project scenario (or conversely, payload weight will decrease). The UAVs can be launched in any weather condition the sensing platform is operating in, assuming the weather is similar between the sensing platform and SAG locations. The survivability and recoverability of launched

UAVs is 100 percent, assuming no losses due to enemy action or during the recovery process.

3. Simulation Method

In order to evaluate the system performance, a first order rough simulation was created using ExtendSim. Variability was added to the simulation using failure decisions for each UAV as it conducts its “deploy, launch, operate, recover” cycle. Triangular distributions for the maintenance downtime (MDT) and UAV travel/loiter times also added variability for each UAV.

SEA23 used a triangular distribution for this simulation because it uses a maximum, minimum, and most likely value, creating a continuous probability distribution with a triangular shaped probability density function. This is useful when data for analysis is such that a mean and standard deviation cannot be attained (Petty and Dye 2013).

4. Inputs

The team based the ExtendSim model on the OV-5b (Figure 14). The ExtendSim model integrates the critical operational issues (COI) into a 72-hour SAG mission. UAV capacity for the SAG, system maintainability, reliability, UAV movement, and UAV loitering times are integrated together to simulate the effectiveness and availability of the UAV communications system with the SAG (Figure 34).

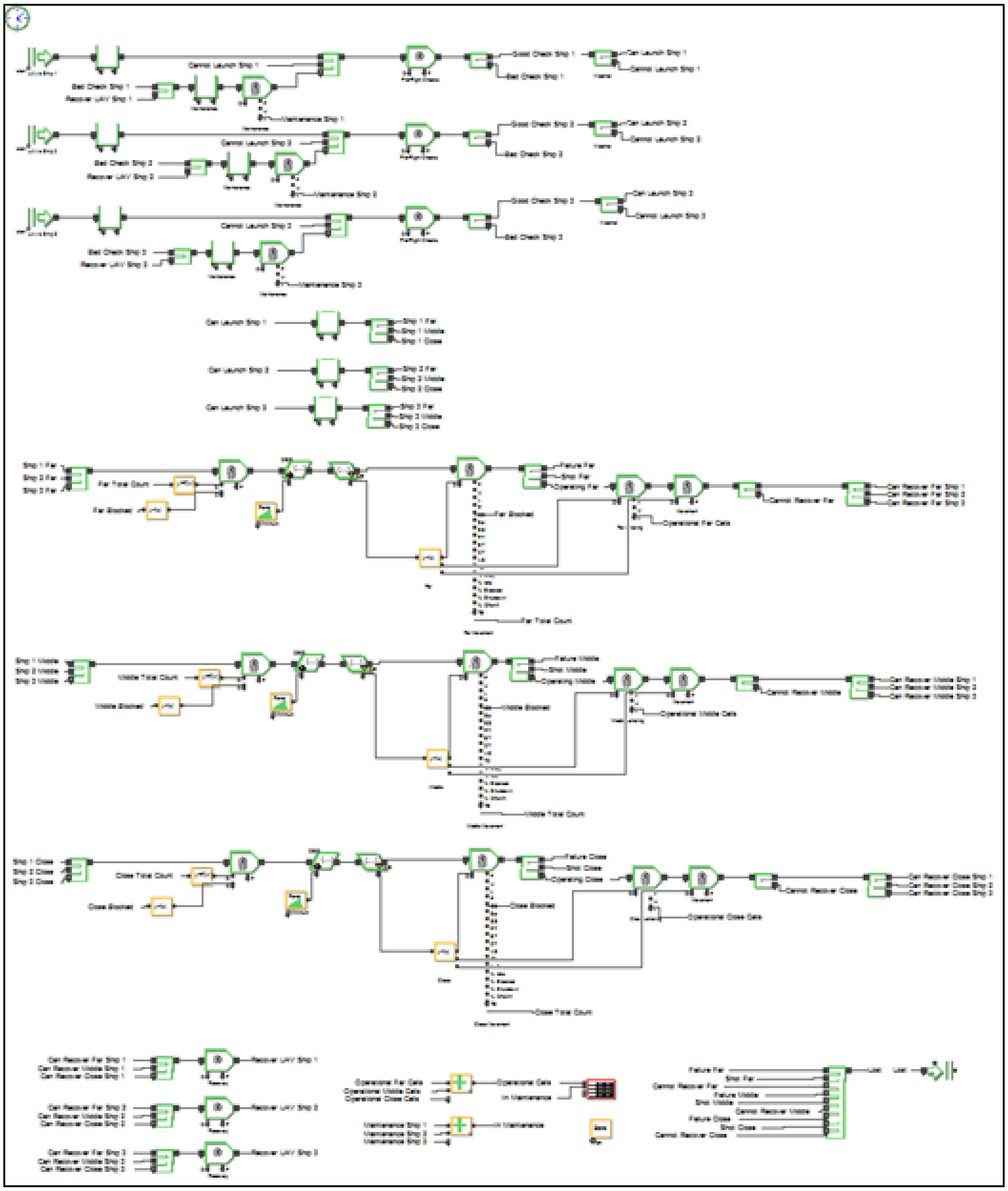


Figure 34. ExtendSim Model Simulating the Number of Operational Nodes Based on UAV type, TDL type, MDT, and Failure Rate.

Figure 35 depicts the deploy phase of the “deploy, launch, operate, recover” cycle. It begins with the input of UAVs carried by each ship in the SAG and ends with a weather decision. SEA23 based UAV input on the number of UAVs from the analysis of SAG hanger capacity for each type of UAV as the input number of items for the simulation.

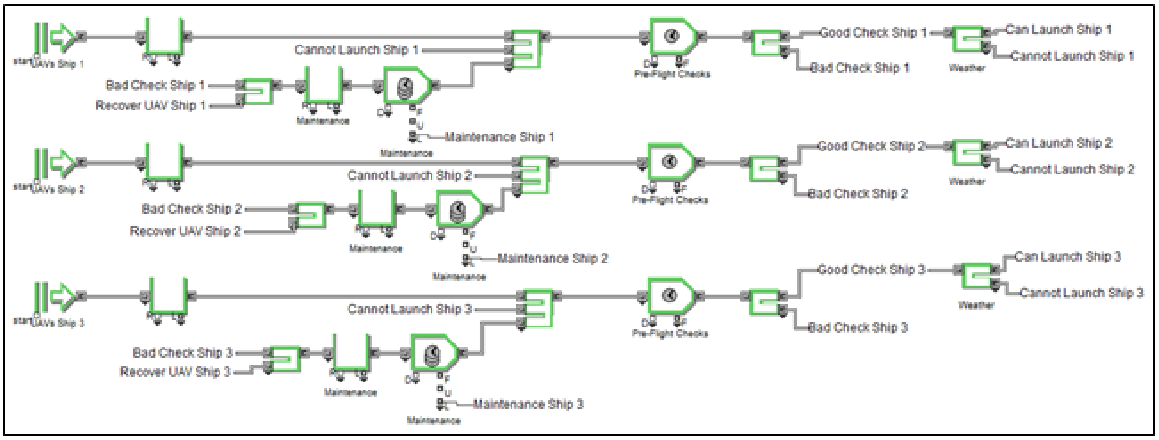


Figure 35. Deploy Phase Of The ExtendSim Model Depicting Sag Carrying Capacity, Maintenance, Pre-Flight Check, And Weather Check.

There are three strings, one for each SAG ship, for the deployment phase. The UAVs are in a queue prior to the pre-flight check. The pre-flight check activity takes five minutes and only allows one UAV to perform the activity on each ship. UAV reliability determined whether the pre-flight check was good or bad. Historical Predator UAV failure rates provide the pre-flight check results. SEA23 used the Predator as a basis for the failure rates. The team assumes that any UAV system used for the communication has 10 to 15 years of operational time, which is similar to the Predator. According to a 2012 article by the American Security Project, Predator failure rates were 7.6 per 100,000 flight hours (Boyle 2012), or $\lambda = 0.000076 \,{}^{failures}\!/_{hour}$. Using equation 12.5 from Blanchard and Fabrycky (2011), the reliability of the UAV over a 72-hour period will be:

$$R(72) = e^{-0.000076 \,{}^{failures}\!/_{hour}(72\,hours)} = 0.995$$

This reliability means that there is a 99.5 percent chance a pre-flight check is good and a 0.5 percent chance it is bad. A failed pre-flight check requires the UAV to get maintenance. The maintenance activity holds an unlimited number of UAVs and immediately services each UAV as it enters the queue. This reliability means that there is a 99.5percent chance a pre-flight check is good and a 0.5percent chance it is bad. A failed pre-flight check requires the UAV to get maintenance. The maintenance activity holds an unlimited number of UAVs and immediately services each UAV as it enters the

maintenance activity block. We assume there is unlimited manpower/materiel for maintenance. A triangular distribution simulates maintenance downtime (MDT). Ship personnel conduct maintenance after each successful UAV recovery. SEA23 used the triangular distribution to "lean" the results towards the minimum and average maintenance times, while still considering that some UAVs will require a long maintenance action at some point during the 72-hour operation. A good pre-flight check results in the UAV going through a weather check decision. The scenario assumes a good weather check. A successful weather check moves the UAV to the launch phase of cycle, while an unsuccessful check results in the UAV going back the "ready" pool.

Figure 36 depicts the launch phase of the deploy, launch, operate, recover cycle. This phase is simply the launch of a single UAV from each SAG ship. Since the successful weather check is always successful, all UAVs enter a single item queue where they are "launched" to either a far, middle, or close node. The optimal flow of UAVs to the far, middle, and close destinations was difficult to model using ExtendSim. This difficulty resulted in a simplification of the launch sequence that limits its ability to allocate more than three UAVs to each far, middle, or close destination, for the first cycle. The model prioritizes UAV destination based on far destinations first, followed by the middle and close destinations, respectively.

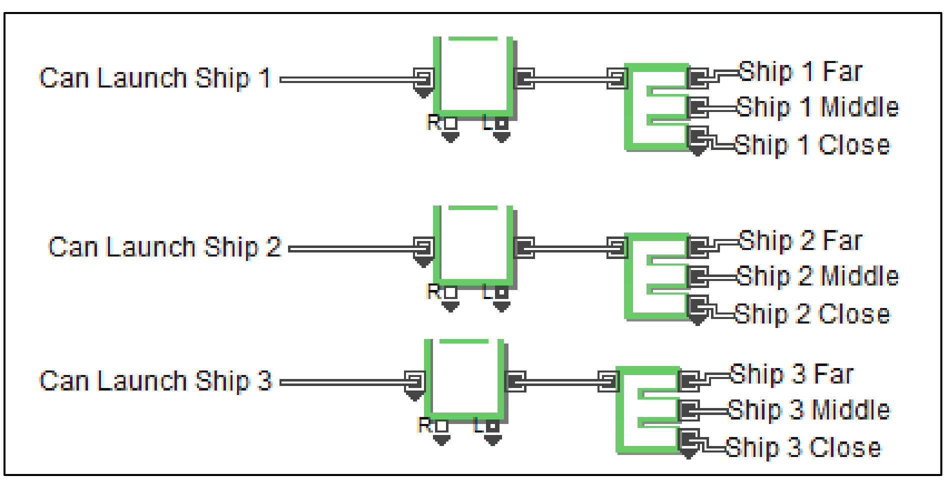


Figure 36. Launch Phase of the ExtendSim Model Depicting Single UAV Launch per Ship and Destination Decision.

The next phase in the ExtendSim model is the operate phase. This phase splits the UAVs into destination strings (far, middle, close) (Figure 37).

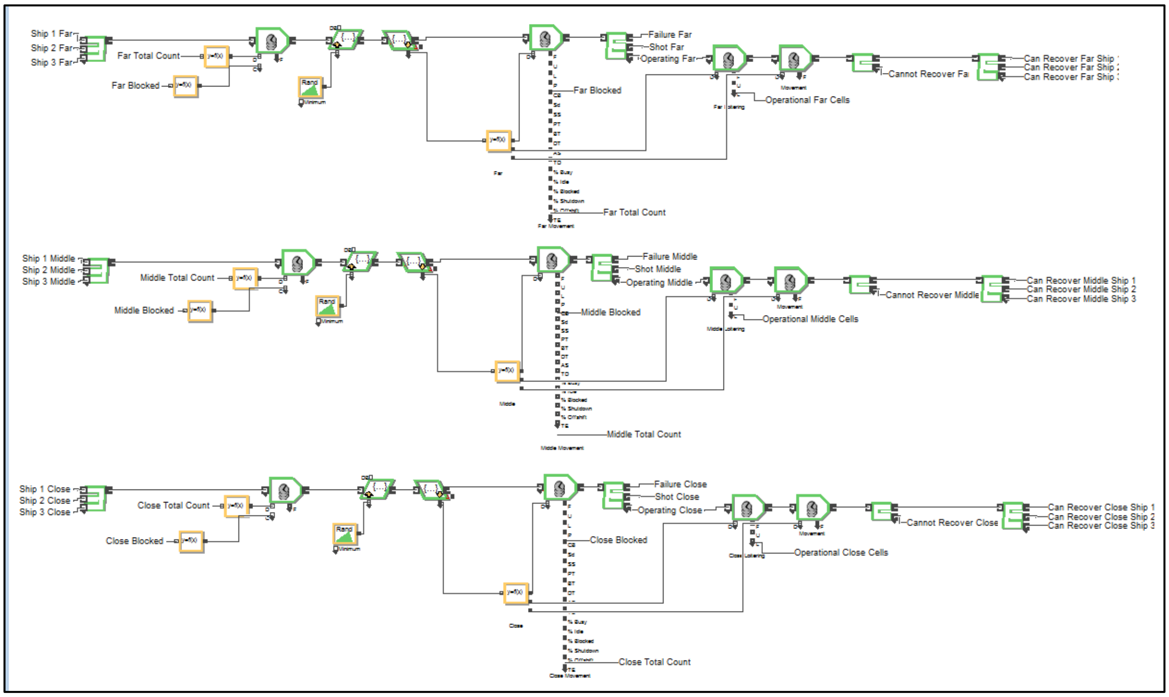


Figure 37. Operate Phase of the ExtendSim Model Depicting Far, Middle, and Close Node Strings Each With "Fly-To" Time, Failure/Shot Decision, Loiter Time, "Fly-From" Time, and Recovery Decision.

An activity that "delays" the UAV from entering the "fly-to" activity simulated constant coverage at each node point. The expected launch cycle for each UAV traveling to the far, middle, or close destinations forms the basis for the "delay" activity. Assuming each "string" of far, middle, or close nodes is equidistant from the SAG, the "delay" was calculated by subtracting the "fly-to" time from sum of the "loiter" and "fly-from" time for each node distance. The "delay" activity has a built in trigger that signals it to "delay" UAVs once five UAVs have entered the "fly-to" activity. It also triggers the activity capacity to switch to zero, stopping launches of UAVs to that node position based on backlog in the "fly-to" activity. Figure 38 describes the ExtendSim statement that triggers the delay and Figure 39 describes the statement that triggers a stop.

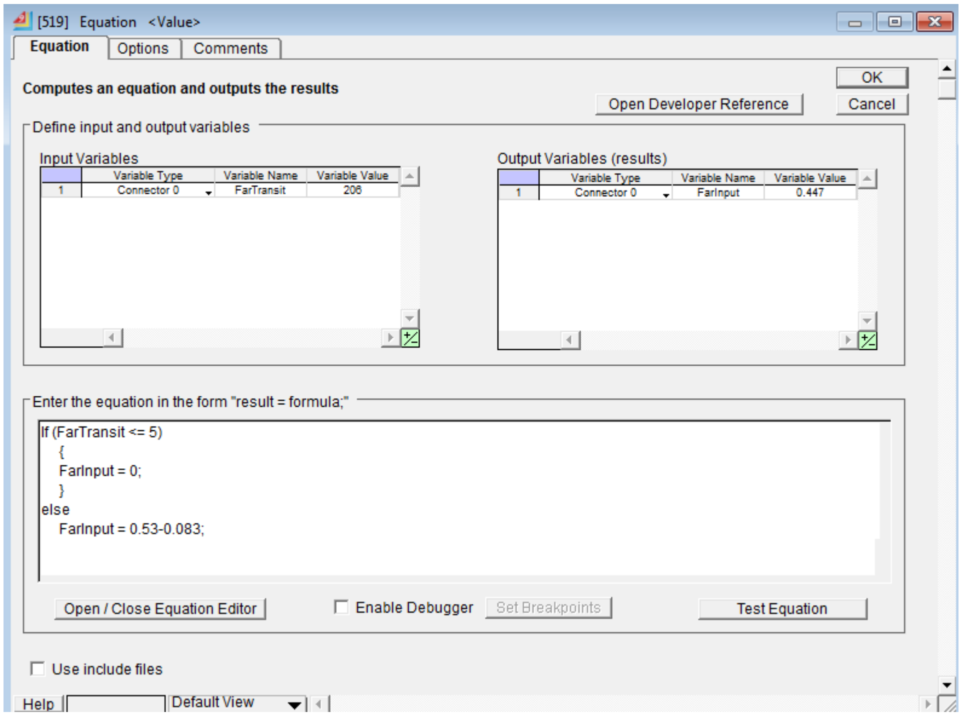


Figure 38. ExtendSim Statement That Triggers a Delay of UAVs in order to Stagger Arrival Time On-Station for the Wasp UAVs Being Sent to the Far Nodes.

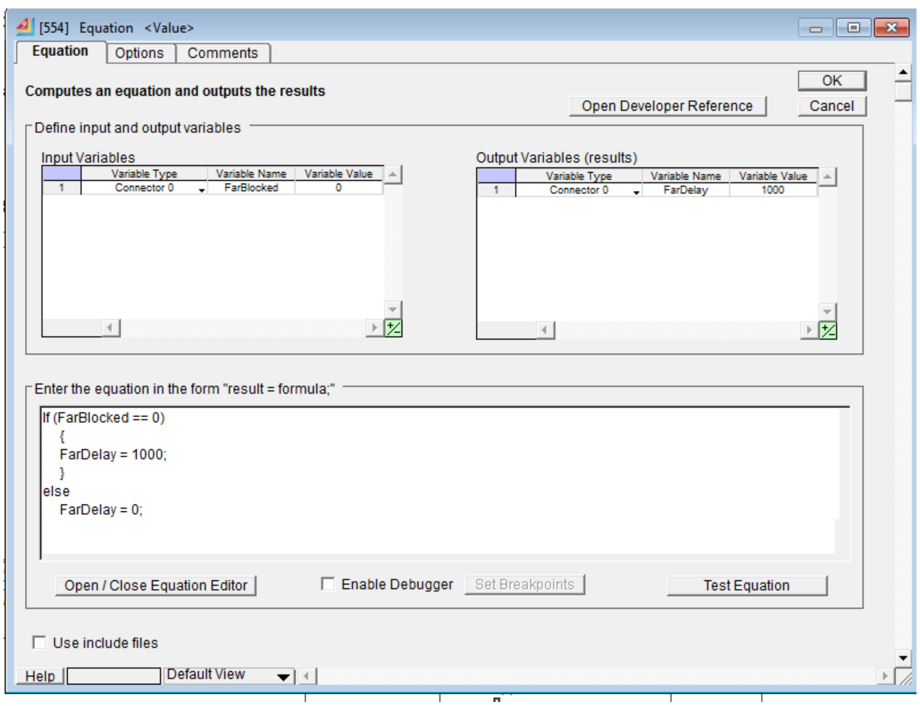


Figure 39. ExtendSim Statement That Triggers a Stop of UAVs Being Sent to the Far Node String.

Table 15 shows the resulting “halt” times. A flaw in the “halt” activity is that it does not know when the first backlog is going to occur in the “fly-to” activity. It is only capable of knowing that a backlog is occurring resulting in too many UAVs sent to the “fly-to” activity, possibly creating a backlog in some simulations.

The movement of the UAVs uses a triangular distribution based on the time it takes a specific UAV to move to the closest, middle, and farthest node. Travel time evaluation, based on TDL types, used maximum and cruise speed of each UAV type and distance to each node position. In order to remain consistent on each UAVs remaining operational time, the model adds a “fly-to” attribute value to each UAV. This attribute value is equal to the value given by the triangular distribution and is carried through the “loitering” and “fly-from” activities. For example, if a UAV is randomly assigned a three hour “fly-to” time, based on the triangular distribution, it will have a two hour “loitering” time and a two hour “fly-from” time. Figure 40 illustrates the equations used to distribute the random “fly-to” times.

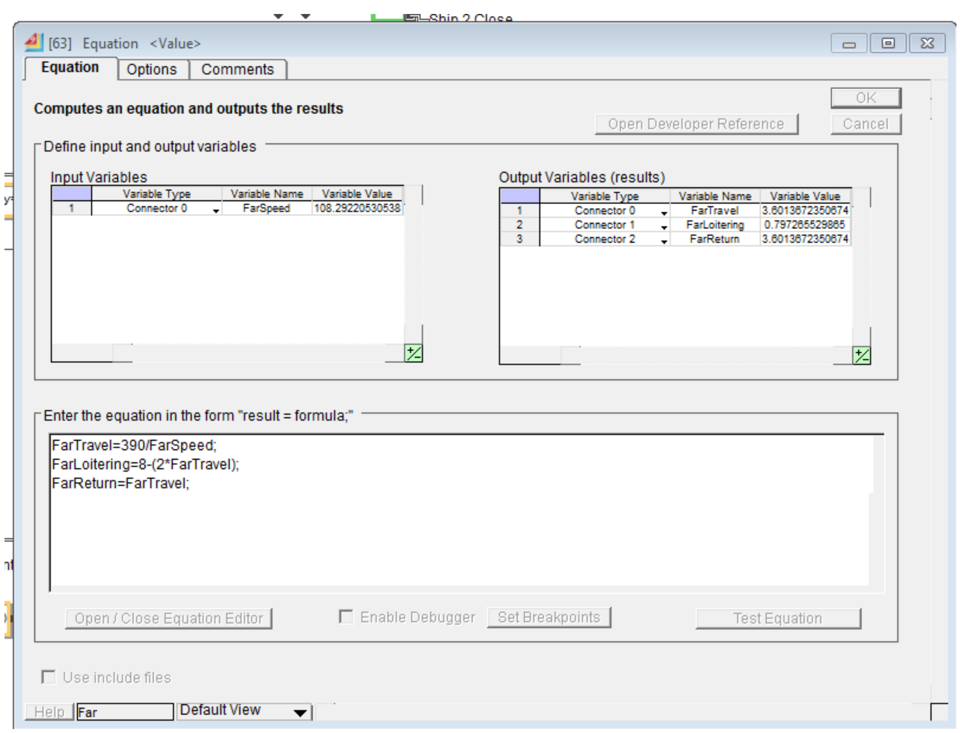


Figure 40. ExtendSim Equations That Assign “Fly-To” Time Attributes to Each UAV.

Table 16 shows the travel and time on station for each UAV, TDL combination, and altitude, while moving at maximum speed. For example, the maximum speed of a DP-5X Wasp is 120 knots (DPI 2016a). The max distance between nodes for Wasp carrying Link-16 is 95 NM. This means it will take

$$t(closest) = \frac{95Nm}{120knots} = 0.8hours$$

for the Wasp to get to its closest position. It will take

$$t(middle) = \frac{250Nm}{120knots} = 2.1hours$$

for the Wasp to get to its middle position, 250Nm being the center of the "moving deadly half-circle." To get to its furthest position the Wasp will take

$$t(farthest) = \frac{500Nm - 95NM}{120knots} = 3.4hours$$

with 500 NM being the location of the sensor and 95Nm being the max distance Link-16 can communicate with the sensor. These values confirm the results of the calculations used in assigning the "fly-to" attribute time to each UAV.

Table 16. Altitude, Travel Time, Time on Station, and Launch Frequency Values for Each UAV and TDL Combination.

	Link-16					CEC	
Smallest Type of UAV	DP-5X Wasp	DP-5X Wasp	DP-5X Wasp (no helos)	DP-5X Wasp (no helos)	DP-5X Wasp (no helos)	DP-14 Hawk (no helos)	MQ-8B Fire Scout
Altitude (ft)	5000	10000	2000	5000	10000	2000	2000
Travel Distance (Nm)							
Close	21.4	237.4	170.2	21.4	237.4	170.2	170.2
Medium	152.4	8.4	280.1	152.4	8.4	280.1	280.1
Far	326.2	254.2	390.1	326.2	254.2	390.1	390.1
Speed, max (knots)	120	120	120	120	120	105	85
Close Travel Time	0.2	N/A	1	1.5	2.1	1.1	1.3
Medium Travel Time	1.3	0.1	2.1	2.1	2.1	2.4	3
Far Travel Time	2.8	2.2	3.3	2.8	2.2	3.8	4.6
Operating Time* (hrs)	8	8	8	8	8	8	8
Close Time on Station	7.6	N/A	6	5	3.8	5.8	5.4
Medium Time on Station	5.4	7.8	3.8	3.8	3.8	3.2	2
Far Time on Station	2.4	3.6	1.4	2.4	3.6	0.4	-1.2
Launch Frequency* (hrs)							
Close Delay	7.4	N/A	5.0	3.6	2.4	4.7	4.1
Medium Delay	4.1	7.7	1.7	1.9	2.4	0.8	1.0
Far Delay	2.5	0.7	0.5	1.1	0.5	0.3	0.2

SEA23 based the operating times at each location on the time remaining after travel time to and from the UAV's loitering location. The far time on station for the MQ-8B Fire Scout is 1.6 hours, which signifies the Fire Scout's inability to achieve the "Fire Web" communications network. This is mainly due to the slow speed and operating time of the Fire Scout. The operate phase utilizes a selector that integrates the probability of failure and survival into the model. SEA23 did not considered the failure rates based on the reliability used for the pre-flight check and the survivability of the UAVs, but they are easily introduced into the model to analyze the effects enemy actions can have on the availability of operational nodes. The operate phase ends with the UAV finishing its "time-from" activity. Each UAV then goes through a decision on whether the UAV can be recovered or not, and then sequentially being sent to Ship 1, 2, or 3 for recovery. The team also did not consider, at this time, the effects a recovery failure has on the availability of UAV nodes.

Recovery phase simulation occurs last in the ExtendSim model (Figure 41). This phase consists of each assigned UAV arriving at their designated ship to be "recovered." SEA23 assumes that recovery of a UAV will take five minutes based on the ease of landing for a vertical takeoff and landing (VTOL) UAV and subsequent movement into a hanger bay. The recovered UAVs return to maintenance, to be sent through the deploy, launch, operate, recover cycle again.

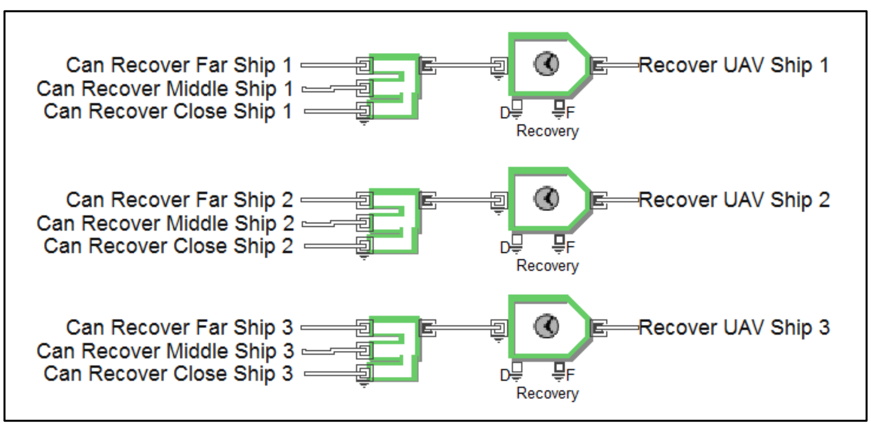
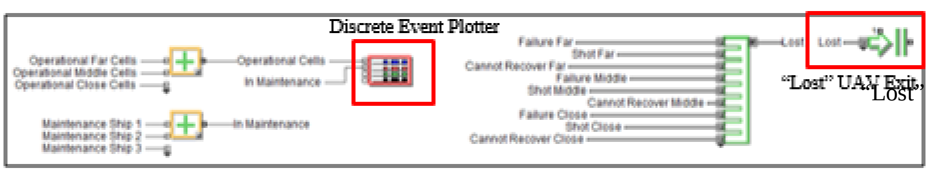


Figure 41. Recover Phase of the ExtendSim Model Depicting the Recovery Activity Time.

5. Outputs

The outputs of the ExtendSim model are a discrete event plotter and “lost” UAV exit (Figure 42). The discrete event plotter shows the average number of UAVs on-station and the average over 30 replications number of UAVs in maintenance at any time during a 72-hour SAG mission. This data determines if the minimum average number of UAVs on-station exceeds the minimum number of nodes needed to create the “Fire Web” (Figure 43). It is also useful in analyzing the effects sustained operations have on the maintenance for the UAV fleet. The “lost” UAV exit shows the total number of UAVs that failed (this simulation is assuming no UAVs are shot down; all UAVs are recovered and all flight times and times on station are completed). We are assuming that UAV failures only affect the maintenance repair time on the ship. This determines the impact reliability and survivability have on availability. The team also analyzed the effects of a failed recovery using this value.



“Lost” UAV Exit

Figure 42. Outputs of the ExtendSim Model: Discrete Event Plotter and “Lost” UAVs.

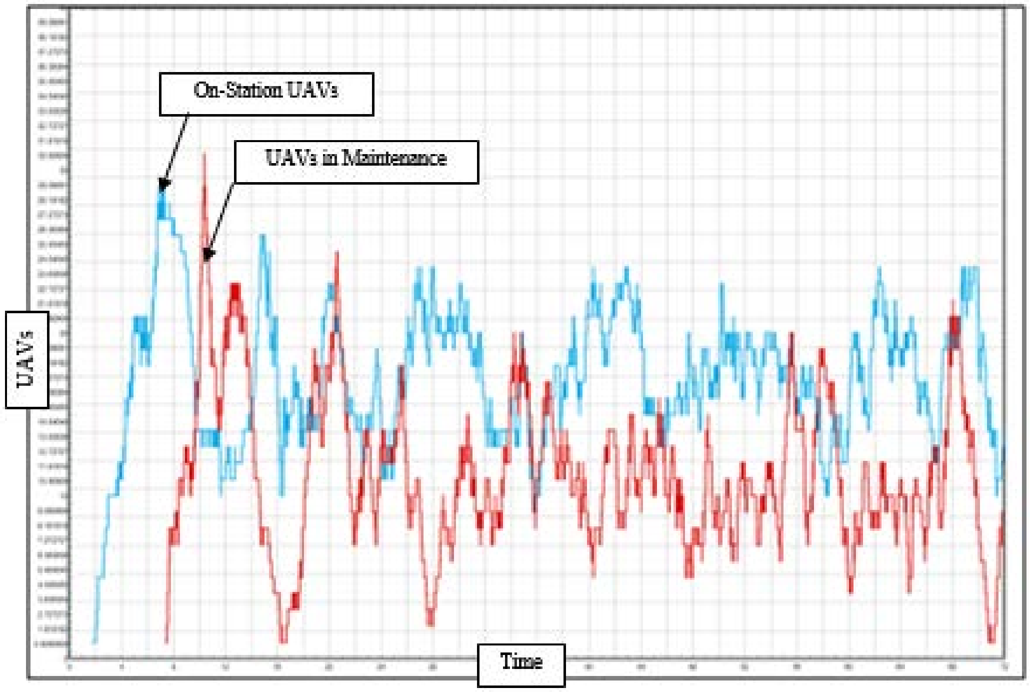


Figure 43. Discrete Event Plotter Results for a Link-16 Equipped DP-5X Wasp and SAG with Organic MH-60R Seahawk Helicopters (Average).

6. Results

From Table 14, 38 nodes were required to maintain the network at full capacity if the nodes operated at 2000 feet. It was easy to see that with any reliability, availability, and maintainability issues, the network cannot function at that altitude with only 45 or 48 nodes. Therefore, the team did not look at the capabilities of the SAG with the manned helicopter for that CONOPS. However, even without the manned helicopter and using 96 Hawks with CEC, it is impossible to achieve the minimum required nodes to operate the network as shown in Figure 44. Figure 44 displays an average of 30 simulations. Due to the stochastic nature of this simulation, no two simulations will result in the exact same graph. The blue line represents the operational nodes. SEA23 defines an operational node as a UAV that is on station. Even though these UAVs are "operational" from the moment they are turned on, the team does not consider them operational for the study until they are on station. The red dots represent the average number of UAVs in maintenance at any

given time. Additionally, the purple and blue dot-dash lines represent the upper and lower 95 percent confidence interval for the average number of operational UAVs. The green dashed line represents the minimum required operational nodes for the network to be 100 percent functional. A major point to realize is that the average number of operational UAVs and the average number of UAVs in maintenance do not add up to the total number of UAVs. There can be over five UAVs transiting to replace just one UAV and several transiting home after their mission. Therefore, none of the figures in the section represents the total number.

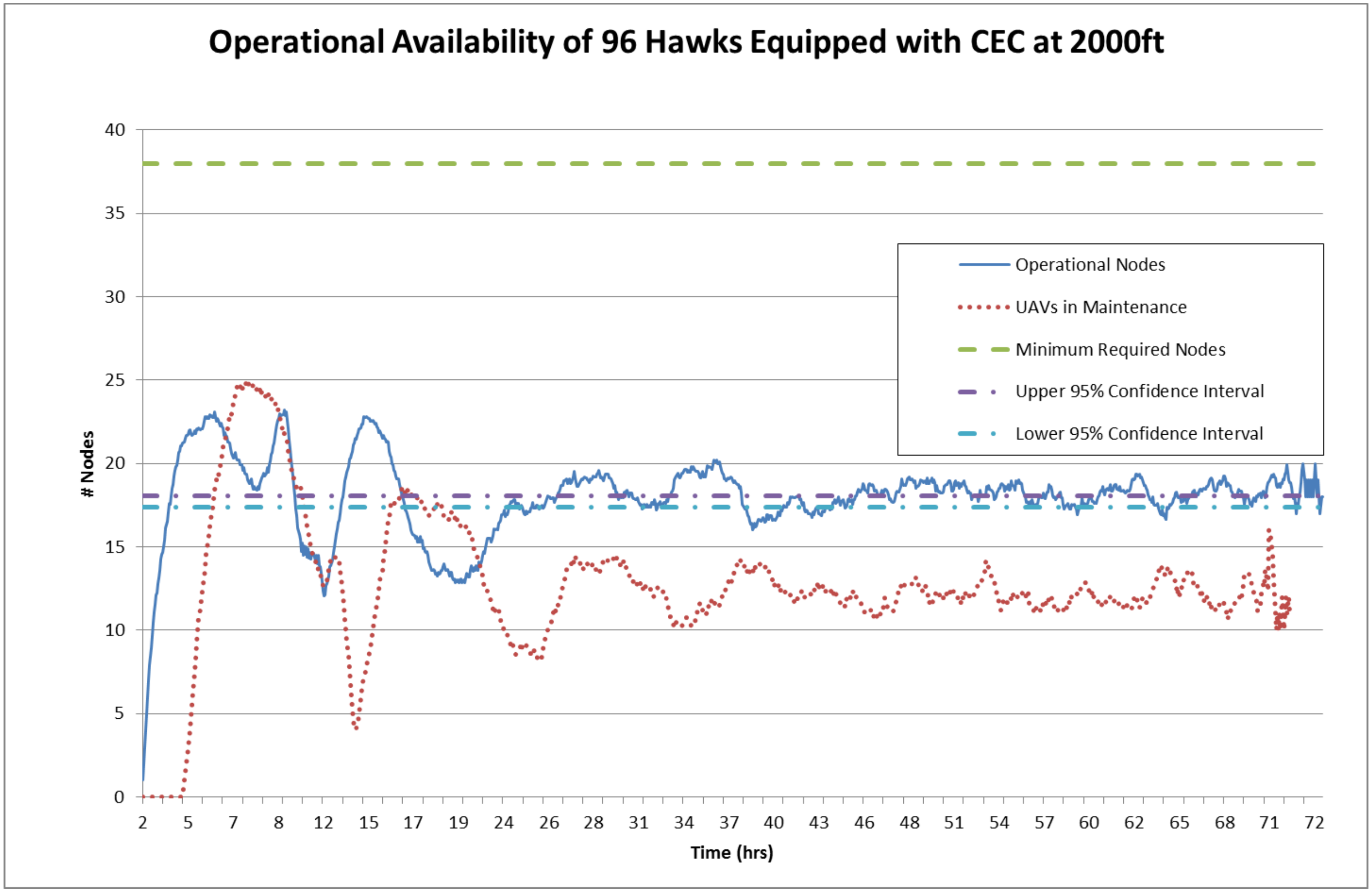


Figure 44. The 96 Hawks' Operational Availability When Carrying CEC at 2000 Feet Altitude.

Since CEC's maximum range is 119 nautical miles, an increase in its altitude gains only 9 nautical miles of range. Without further research, CEC is not a viable consideration. Additionally, the team looked at Link-16 operating at 2000 feet with 90 UAVs available in the SAG. The team also analyzed Link-16 operating at 2000 feet with 90 UAVs available in the SAG. This was not a viable alternative due to the number of nodes required to transit long distances. It is impossible to meet the required number of nodes because many will begin maintenance early and limited launch platforms do not enable replacements quickly enough to cover the transit distance. Figure 45 shows that the Wasp and Link-16 combination does not work at 2000 feet.

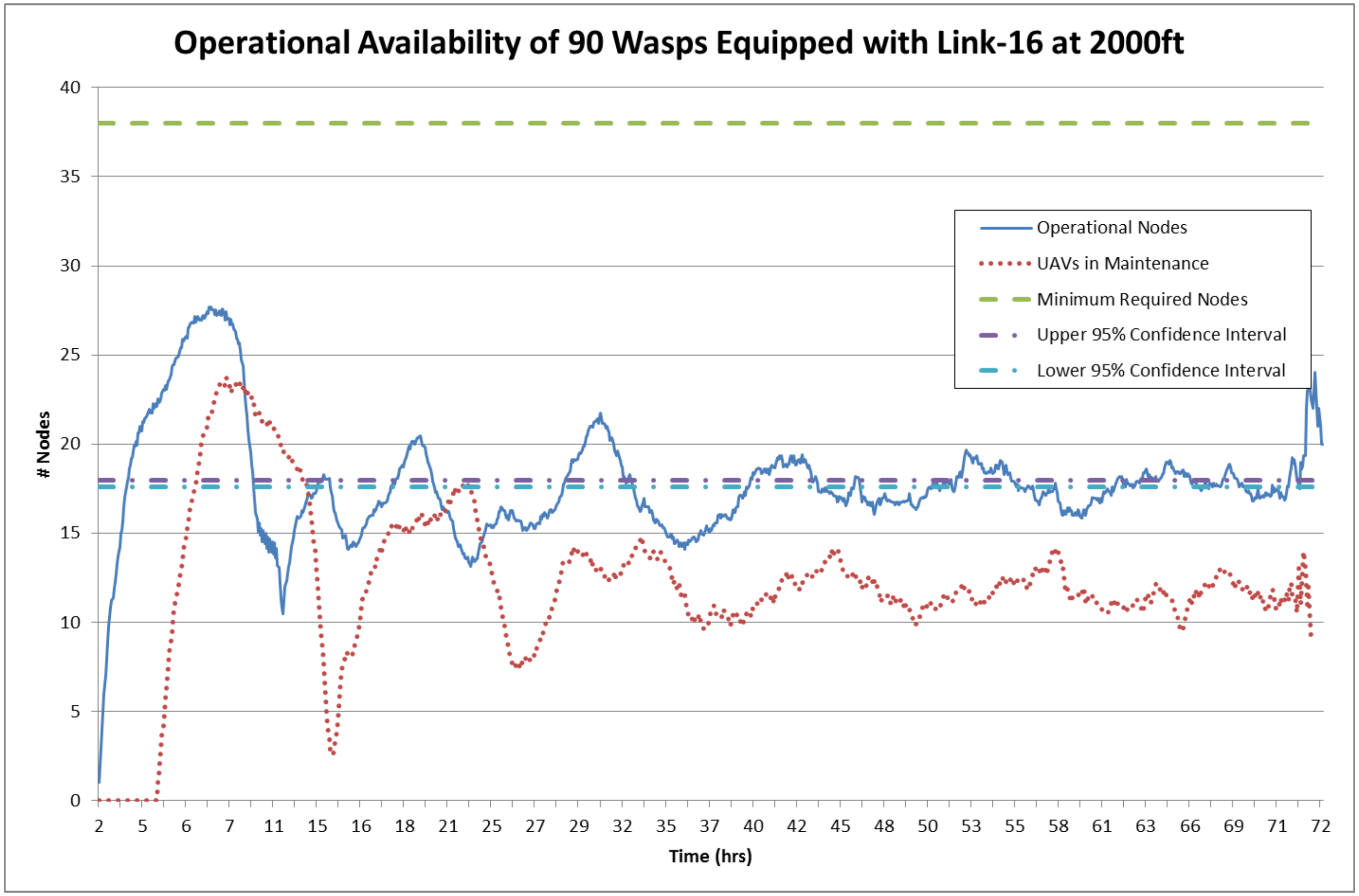


Figure 45. The 90 Hawks' Operational Availability When Carrying Link-16 at 2000 Feet Altitude.

At 5000 feet, the number of required nodes decreases to 16. However, these are also unachievable by both the 45 node and 90 node configurations of Wasps with Link-16. This is because of the number of nodes still required to be airborne at a single time in order to fill a particular slot and limited launch platforms to refill them. In this simulation, there are still considerable distances that the UAVs must travel even if they are benefiting from better on-station times. This increased distance, and its associated failure rates, means that many UAVs must be transiting at any given time to replace those on station. A large number of these UAVs are not operational either in the simulation's definition, but are flying to relieve an on station UAV or in transit home. Figures 46 and 47 illustrate this capability gap.

A simulation at 10000 feet showed much better results than the previous simulations. An alternative exists to use DP-5X Wasps equipped with Link-16 that will also achieve a completed network. The team first looked at 45 nodes available in the SAG (Figure 48).

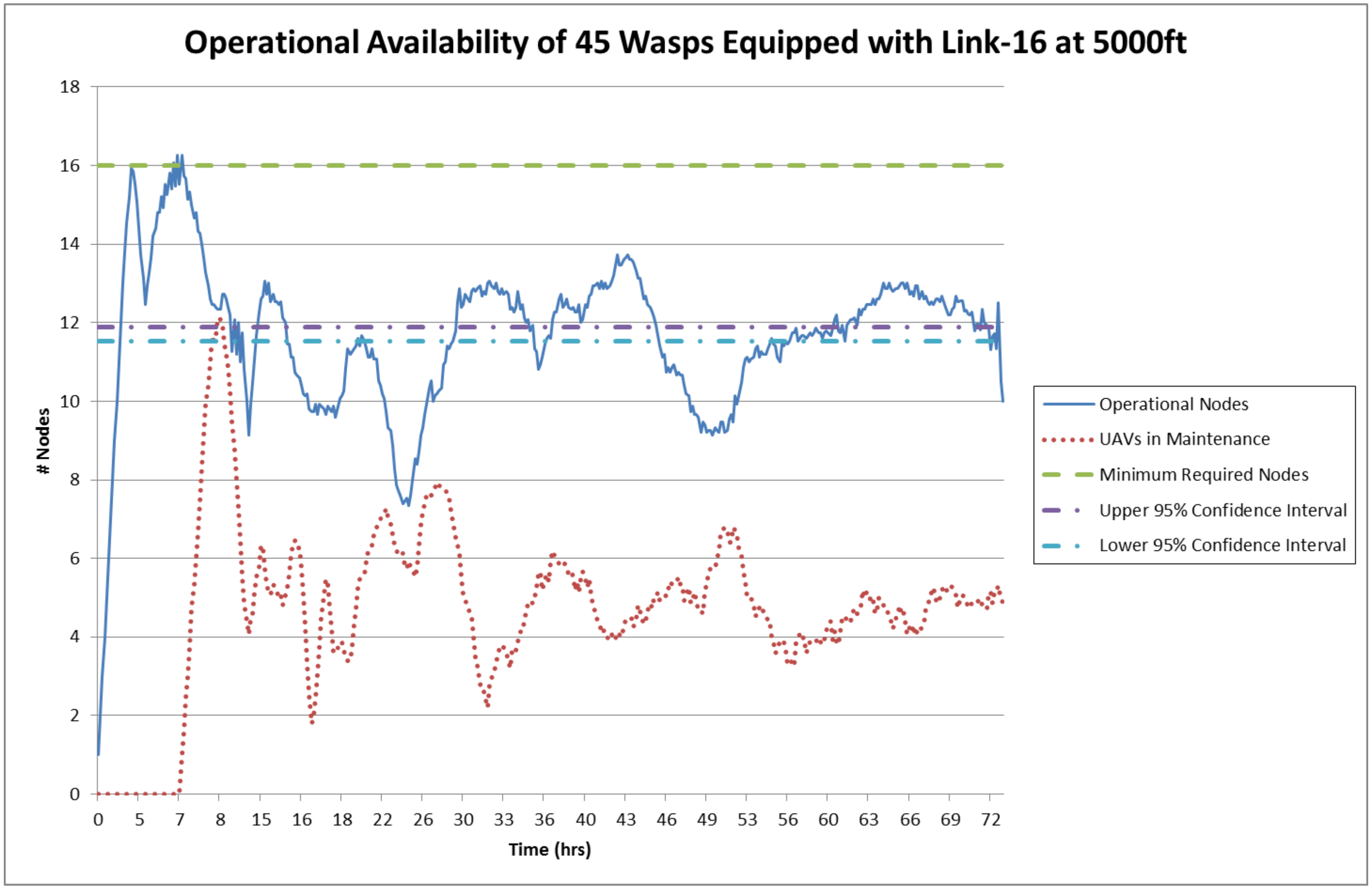


Figure 46. Average of 45 Hawks' Operational Availability When Carrying Link-16 at 5000 Feet Altitude.

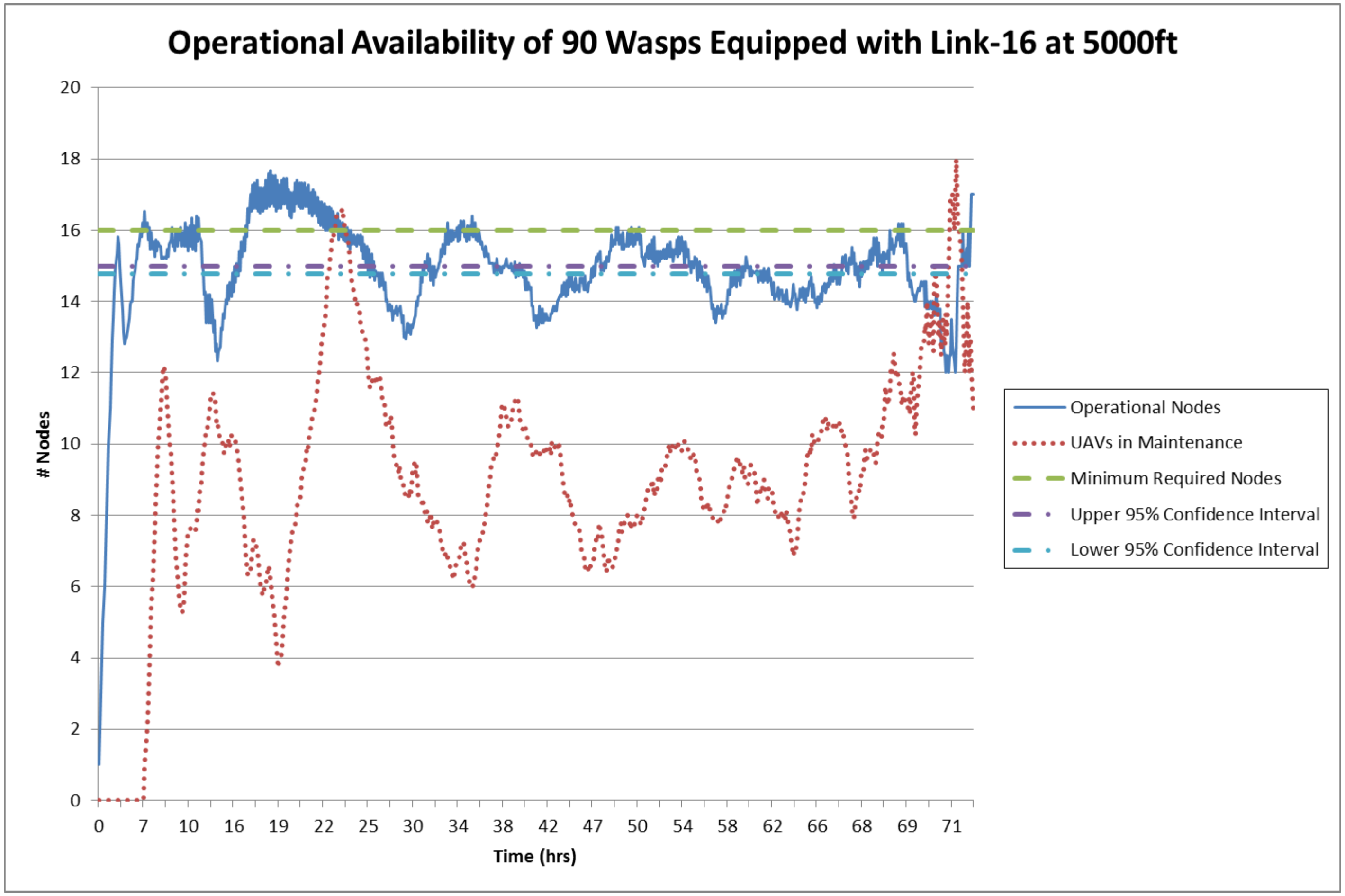


Figure 47. The 90 Hawks' Operational Availability When Carrying Link-16 at 5000 Feet Altitude.

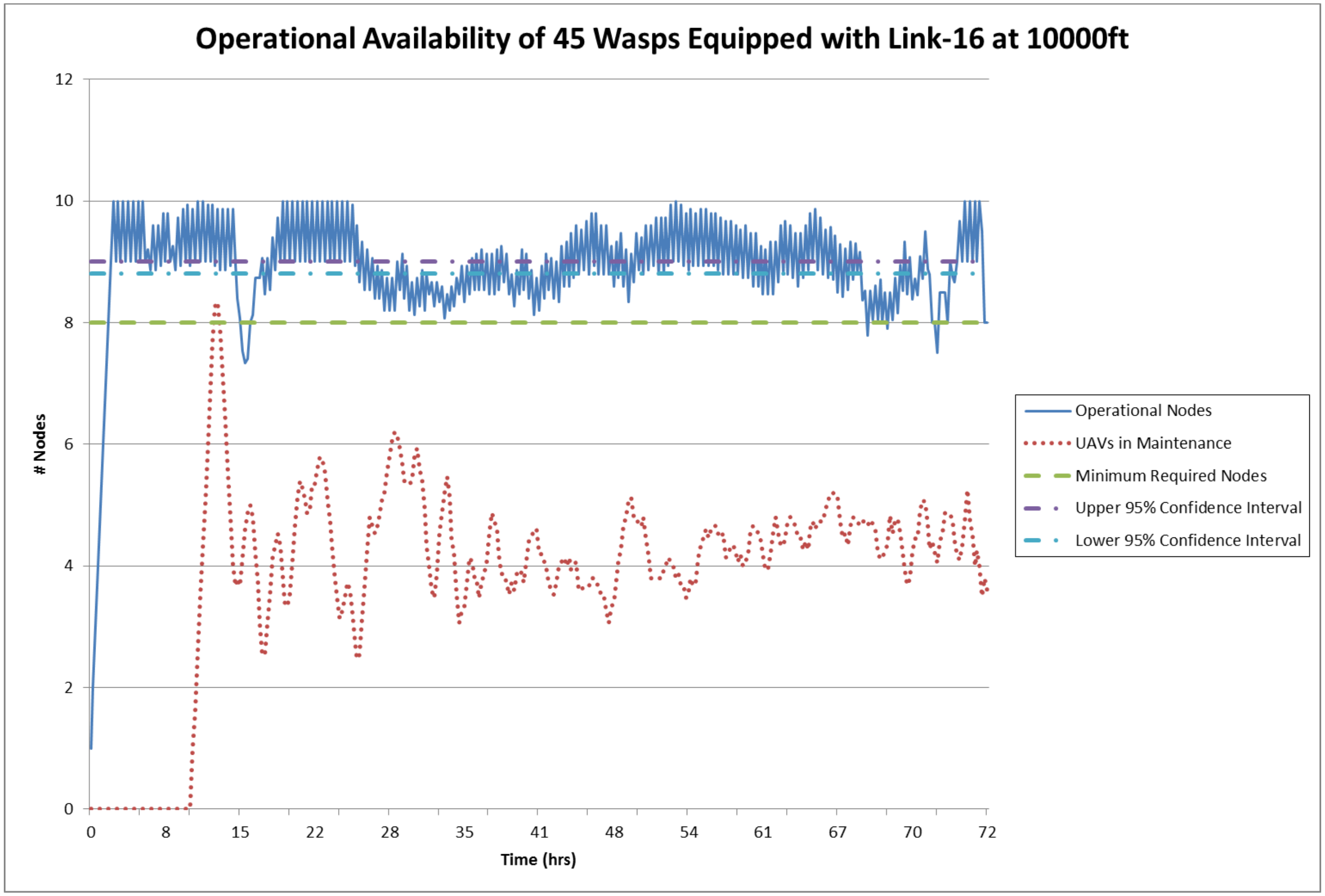


Figure 48. The 45 Hawks' Operational Availability When Carrying Link-16 at 10000 Feet Altitude.

During the 5000 feet simulations (Figures 46 and 47), the number of nodes airborne is higher than in the 10000 foot simulation (Figure 48). By design, the simulation concept of operations is much different. In the 2000 and 5000 foot simulations, the node placement was essentially designed as having a close, middle, and far ring (referenced to the SAG). This meant that several UAVs did not have to travel great distances and were easy to keep operational. When the simulation increased to 10000 feet, the nodes (on average) are required to travel greater distances than in the previous simulations. The model was not able to take advantage of having close nodes to fill. The previous simulations also have more nodes that are close to the ship increasing the ship's ability to launch and replace them. In this simulation, all of the nodes must travel at least 200 nautical miles therefore the model experiences greater losses in the form of transit times. A SAG can achieve a 0.98 operational availability using 45 nodes. The minimum number of nodes required falls below the lower confidence limit for the average operational nodes indicating that there is a good chance the system will have the required number of nodes on average. However, there are few places where the network will drop below eight nodes. Therefore, even when the node is available in a 100 percent capacity, it will only experience a small coverage gap losing only one node. Proper tactical level planning will account for these gaps.

In the 90-node configuration, the system can achieve a 0.97 operational availability for the 72-hour period. The SAG can continue launching nodes and even with 35 nodes in maintenance, it can continue to operate effectively. Figure 49 depicts the 90-node simulation.

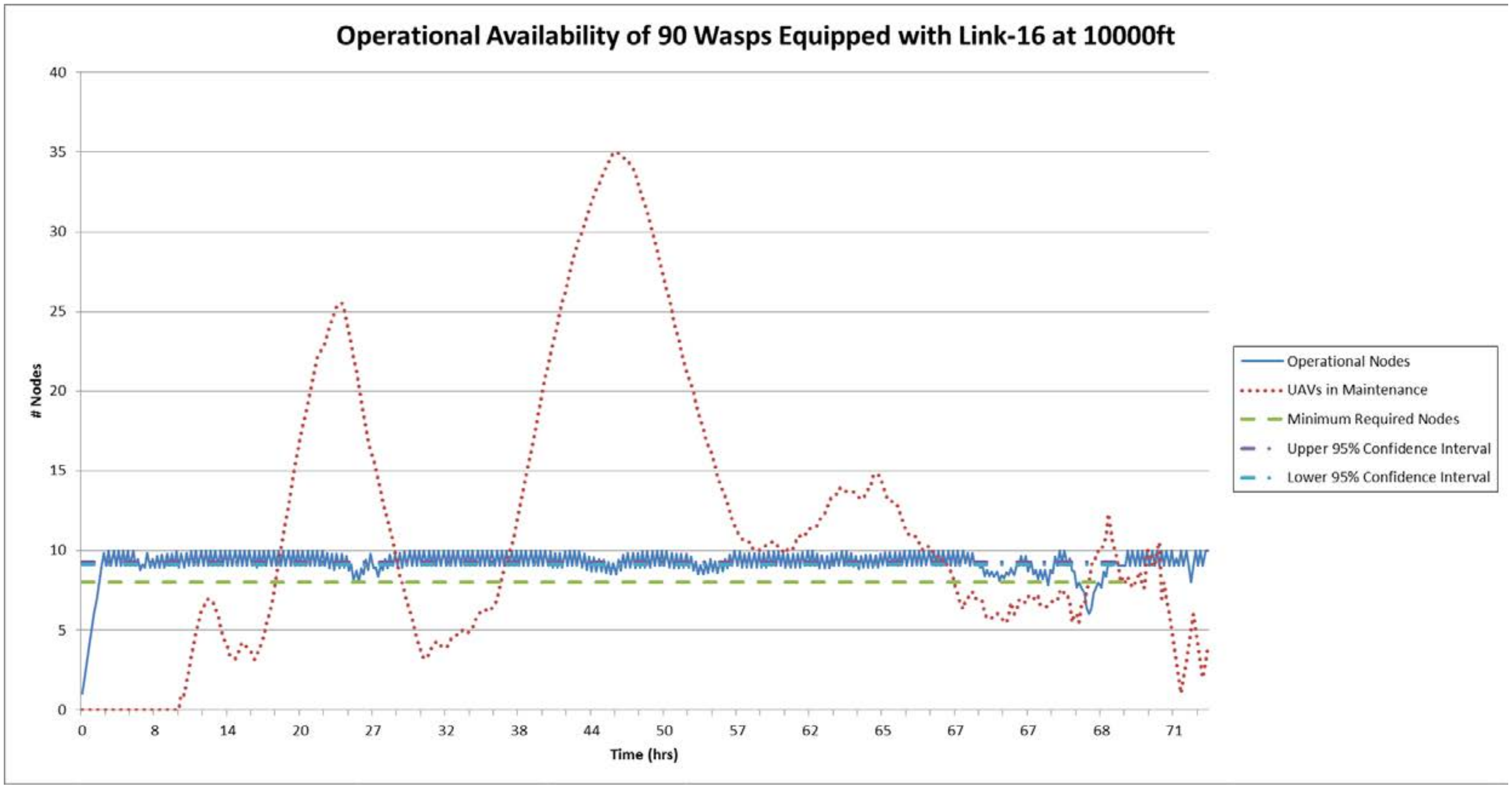


Figure 49. The 90 Hawks' Operational Availability When Carrying Link-16 at 10000 Feet Altitude.

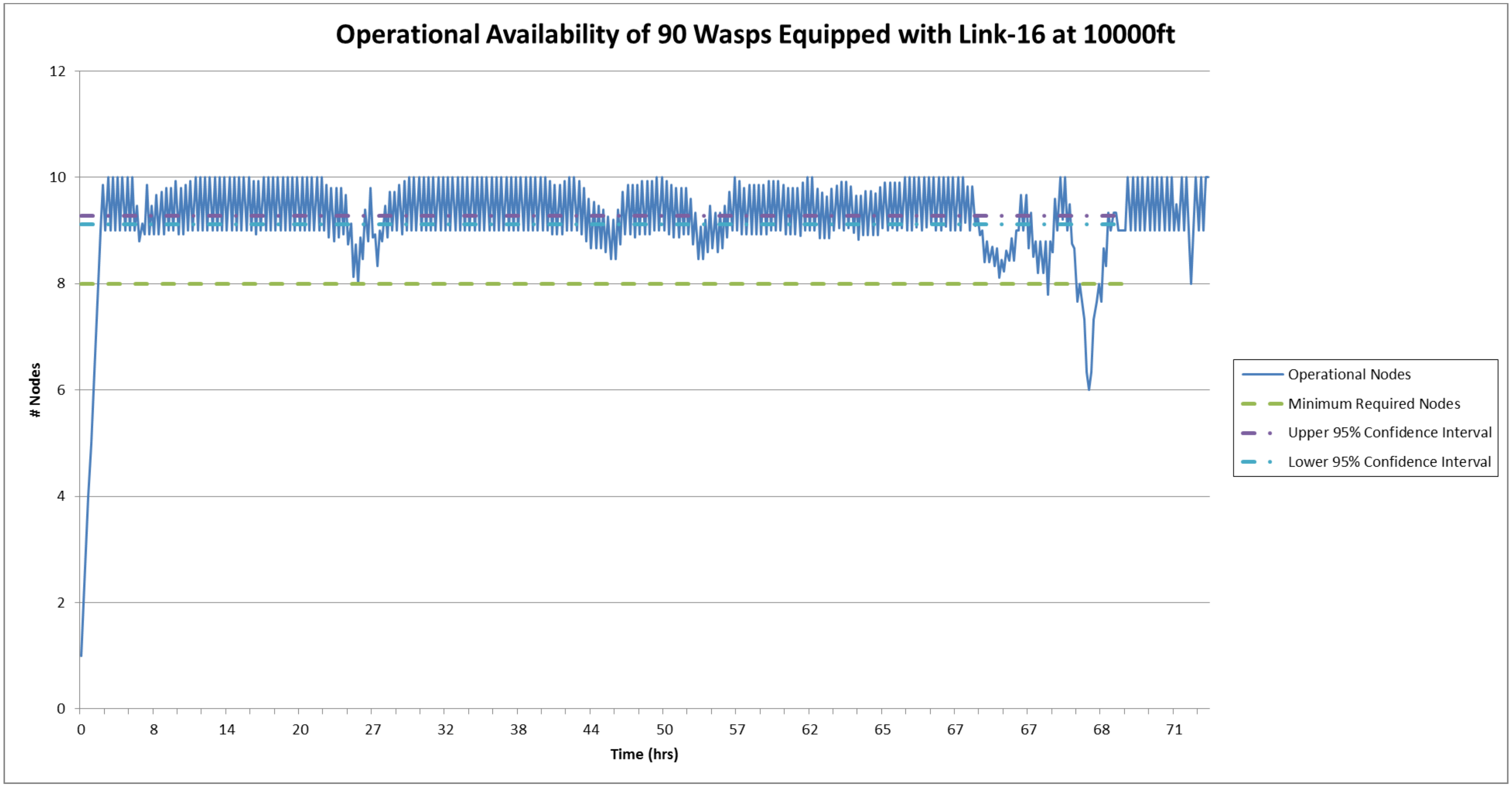


Figure 50. Operational Availability of 90 Wasps Equipped with Link-16 at 10000 Feet with UAV Maintenance Removed.

The 10000-foot simulation with 90 UAVs available gave the best result. The worst-case scenario is an infrequent single node outage in coverage. The graph becomes difficult to read because of the number of UAVs in maintenance during this simulation resulting in a skew that makes the operational nodes difficult to identify. Figure 50 depicts the same simulation with maintenance removed to enhance readability. In this simulation, the minimum number of nodes required is below the lower 95 percent confidence interval for the average operational nodes. This confirms the finding of a 0.98 operational availability.

There are noticeable dips in availability at least every 24 hours in both sets of the 10000-foot simulation as seen in Figures 48, 49, and 50. This is associated with spikes in UAV maintenance as backlogs occur (although delayed). SEA23 wanted to investigate what the operational availability will be for the first 24 hours. The team wanted to test a system to its limits but a 24-hour scenario is also possible. The operational availability for a 24-hour and 45-node scenario is 0.97, showing a slight drop from the initial result. The same period for the 90-node scenario increases operational availability to 1.0 showing the effect those additional on-hand nodes has when the system is under stress for a longer period.

7. Recommendations

Based upon Table 13, the "Other" network comprised of lightweight, low-power networks is not yet feasible, but requires further research. The UAVs considered are very small for their relative capabilities and there is no way to fit enough in a three (or four) ship SAG. The 10000-foot DP-5X Wasp with Link-16 option showed that it was feasible to retain the manned helicopter capability and meet the system of systems requirements. There are three basic alternatives from this study:

1. Add additional ships to the SAG to fly lower altitude missions
2. Choose to implement 45 DP-5X Wasps with Link-16, retaining the manned MH-60 capability
3. Choose to implement 90 DP-5X Wasps with Link-16 and add additional ships to retain manned MH-60 capability

Any further study of Option 1 should include different combinations of ships. For a solution that is feasible to study and implement in the next 10–15 years, SEA23 recommends option two. Since Options 2 and 3 provide roughly the same availability, the capability advantages by retaining the manned helicopter are superior to the buffer that having double the amount of UAVs will provide. However, a cost analysis must verify this recommendation.

VIII. COST ESTIMATION

To determine the feasibility of the recommended design solution for the proposed SOS, cost estimation is necessary. In addition to technical requirements of a system, the acquisition plan for procuring the system is of the utmost importance. For the proposed design recommendation, SEA23 conducted a cost analysis that provides an estimate for the DP-5X Wasp/Link-16 combination and a comparison of two SAG complement options.

A. TACTICAL DATA NETWORK COST ESTIMATE

The proposed design is comprised predominantly of a platform and the physical hardware for the chosen tactical data link. These two system components will generate an overall system cost estimate. The tactical data link in question is currently in use by the U.S. Navy. Given this, the published acquisition report, which contains the cost data for the system, is usable in the cost estimate for this selected design. The system that provides Link-16 capability is the Multifunctional Information Distribution System Joint Tactical Radio System (PEO, IWS 2015a). Fig 51 shows the MIDS JTRS per unit cost from the SAR (PEO, IWS 2015a).

Unit Cost Report

Item	BY 2003 $M Current UCR Baseline (Nov 2013 APB)	BY 2003 $M Current Estimate (Dec 2014 SAR)	% Change
Program Acquisition Unit Cost			
Cost	3031.0	3196.7	
Quantity	6233	6399	
Item	0.486	0.500	+2.88
Average Procurement Unit Cost			
Cost	1393.5	1508.6	
Quantity	5745	5851	
Unit Cost	0.243	0.258	+6.17

Figure 51. Unit Cost Report. Adapted from PEO IWS (2015a).

Figure 51 shows the average procurement cost for a single unit in FY03$ as $243,000 and a 2014 SAR estimate of $258,000. Figure 52 shows the average annual operating and support cost for the MIDS in FY03$K that gives an estimate of approximately $10,240 per year (PEO, IWS 2015a). Combined, the purchase price and one year of operating support yield an approximate cost of $268,240 FY13 (PEO, IWS 2015a).

Annual O&S Costs BY2003 $K		
Cost Element	**MIDS Average Annual Cost Per Terminal**	**N/A (Antecedent)**
Unit-Level Manpower	0.250	--
Unit Operations	0.000	--
Maintenance	0.440	--
Sustaining Support	4.120	--
Continuing System Improvements	5.430	--
Indirect Support	0.000	--
Other	0.000	--
Total	10.240	--

Figure 52. Annual Operating and Support Costs. Adapted from PEO, IWS (2015a).

Figures 53 and 54 show a visual comparison of the two along with a 20-year total procurement/operating and support cost for a single system. A cost comparison in FY16 dollars provides a more accurate comparison. SEA23 used the Joint Inflation Calculator created by the Naval Center for Cost Analysis for cost conversions. SEA23 used the Other Procurement Navy (OPN) appropriation/cost element to determine the inflation indices.

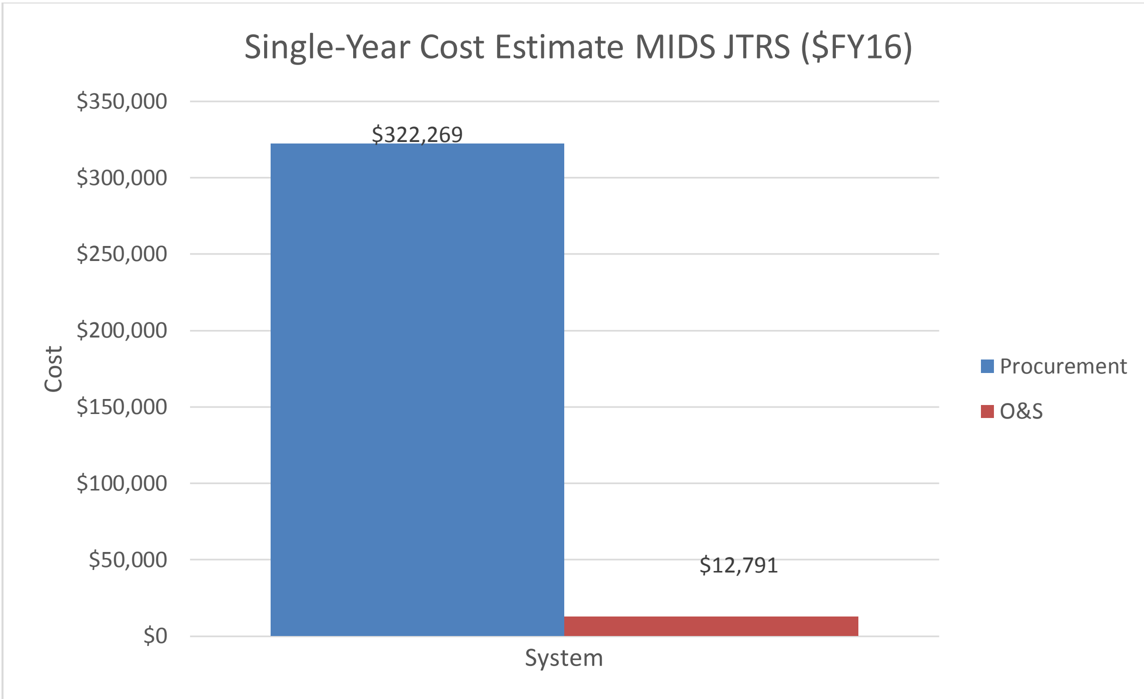


Figure 53. Single-Year Cost Comparison in Fiscal Year 2016 Dollars.

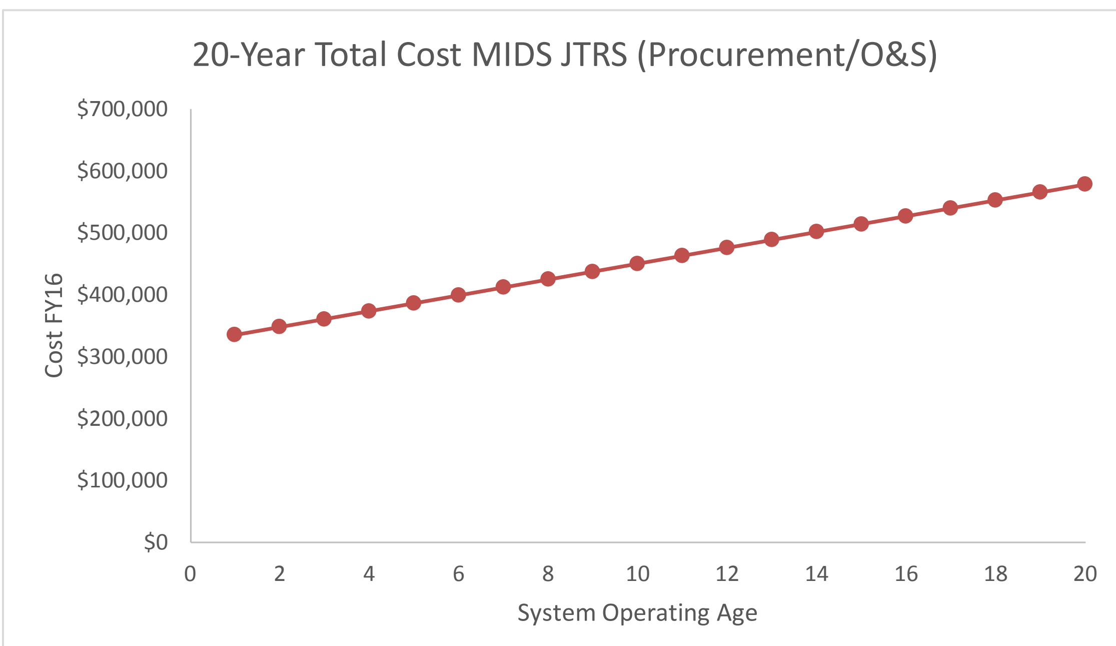


Figure 54. 20-Year Total Cost including Procurement and Operating and Support in Fiscal Year 2016 Dollars.

Figure 54 shows the cost breakdown of procurement and operation and maintenance for a single year. Projections for a 20-year life cycle of the system show a steady increase. Compared to similar systems, the cost of a single system over a 20-year life is relatively affordable.

B. UAV COMPONENT COST COMPARISON

The second element of the proposed design is the platform. As previously discussed, platform selection was based on size and requirements. The DP-5X Wasp allows for a large number of units to be carried onboard a single ship. The manufacturer for this system is Dragonfly Pictures, Inc. located in Essington, Pennsylvania. Cost information for large production quantities is currently unavailable; however, the manufacturer provided assistance in estimating an approximate range for these costs.

SEA23 and the manufacturer agreed that the UAS Roadmap 2005 was the best estimate for a single production cost. The UAS Roadmap states that the "empty weight cost" estimate is a commonly used metric that is standard in the aviation industry (OSD 2005). It states that an approximation of these units will cost roughly $1500 per pound of empty weight and $8,000 per pound of payload capacity (OSD 2005). The payload weight concurs with the previous data obtained from the selected acquisition report for the MIDS JTRS. Using this metric for empty platform weight, a projected cost for the Wasp, as estimated by the manufacturer is approximately $550,000 to $750,000.

Although these figures are rough estimates provided by the manufacturer, the projected ranges are well under the actual costs for most other comparable UAV systems currently employed within the DOD. Considering the platform will need to be purchased in a large quantity (at least units per SAG), the cost per unit will decrease given the large quantity being mass-produced. The manufacturer concluded that large-scale production reduces the cost per unit by approximately one half. This will result in a price range for each UAV to be $275,000 to $375,000.

The manufacturer previously conducted a cost analysis on a similar and comparable UAV. This cost analysis included production cost drivers, reserve per hour costs, and direct operating costs per hour. Figure 55 shows the estimated costs. An item

of note is that the listed fixed annual cost regarding liability insurance and hull insurance applies to a non-government operated vehicle leading to their omission in the analogous cost estimate.

Because SEA23 calculated the platform production cost separately, it is important to note that the cost estimation does concur with the cost estimation of a single unit as shown in the figure below. The data of significance is the cost of operation per hour. Excluding the fixed cost, the total operating cost per hour is approximately $280 (Figure 55). Total yearly operating time is difficult to predict and is heavily dependent on the number of deployed units. Based on the developed concept of operations, SEA23 used a 72-hour operation as the basis for the cost estimate.

Comparable UAV Estimated Operating Costs			
Cost Drivers	**Units**		**Amount**
Wrap Rate for Labor		$	59.82
Average Flight Time between pre-flight inspections	hrs		5.30
Time for Inspections per flight	hrs		0.1
Time to Perform 100 hr Inspection	hrs		40
Average Fuel Burn per Hour	lbs		14
Price of Fuel Per Gallon	$/gal	$	6.00
Mean Time Between Failure (MTBF)			1840
Mean Time To Repair (MTTR)			1
Time Between Overhaul (TBO) - Turbine	hrs		12,000
Turbine Overhaul @ 12,000 hrs	$		125,000
Time Between Overhaul (TBO) - Aircraft	hrs		2,000
Overhaul as % of new price	%		30%
Flight Hours per year (30 days * 24 hrs/day)	hrs		720
Purchase Price		$	897,389.46
Fixed Annual Costs			
Liability Insurance		$	3,072.00
Hull Insurance		$	16,575.00
FIXED COST PER YEAR		$	19,647.00
Reserve for Overhaul			
12000 Hour Turbine Overhaul		$	10.42
2000 Hour Aircraft Overhaul Parts Kit		$	134.61
Labor (240 manhours @ $100/hr)		$	13.04
RESERVE PER HOUR		$	158.07
Direct Operating Cost			
Fuel		$	84.91
Oil		$	0.38
Pre-flight Inspections		$	11.29
Scheduled and Unscheduled Maintenance (40hr/100 flight hr x wrap rate)		$	23.93
DIRECT OPERATING COST PER HOUR		$	120.50
Total Operating Cost			
Fixed Cost per Flight Hour based		$	27.29
Overhaul Reserve Per Hour		$	158.07
Direct Cost per Flight Hour		$	120.50
TOTAL OPERATING COST PER HOUR		**$**	**305.86**

Note: The above estimates are approximate and will vary with type of use, maintenance, environmental conditions and prices. This information is for comparison only and not an offer to sell. Referenced prices are subject to customer requirements.

Figure 55. Estimated Operating and Support Costs in Fiscal Year 206 Dollars.

A SAG can carry 45 or 90 nodes based on available storage space. Given the selected operating altitude of 10,000 feet, the number of nodes that need to be operational

to maintain network coverage over a 72-hour mission varies. Table 17 shows a comparison of the two feasible options based on operational availability and the resulting required number of nodes.

Table 17. 72-Hour Continuous Coverage Mission Cost Estimate

Operating Altitude (Ft)	Nodes on SAG	SAG Complement Procurement Cost Estimate	Operational Availability Gained	Number of Desired Instantaneous Operational Nodes	Average Instantaneous Operational Nodes (Based on Operational Availability)	Total Operating Hours	Total Mission Operating Cost
10k	45	$14,625,000	**0.98**	8	7.84	564.48	$158,054
10k	90	$29,250,000	**0.97**	8	7.76	558.72	$156,442

Table 17 highlights the main tradeoff analysis concerned in equipping a SAG with this system. These two combinations of operating altitude and instantaneous number of nodes in the air produce an operational availability and a cost to achieve it. An obvious conclusion is that equipping the SAG with 90 units instead of 45 units costs twice as much initially when procuring the nodes. Price increases when going from 45 to 90 project to be less than the average cost of a single manned helicopter asset. As shown, the operational costs for a single 72 hour mission almost double while the operational availability is roughly the same. Due to the stochastic nature of the simulation, SEA23 treated 0.97 and 0.98 to be statistically the same. This may not show an actual loss in performance for the 90 UAV simulation. There is no cost benefit given the fact that availability does not change, when compared to the loss in capability of removing a manned helicopter asset from the SAG.

It is important to remember that the operational availabilities shown are slightly misleading because they guarantee complete network coverage. If there is a coverage gap in the network at any given time, even if less than 0.5% of the geographic area, the model reports no availability. The availability of the network is much higher than these reported numbers because of this.

Another data point to consider is the choice of the 72-hour mission to model the operational availability of the system. Given the conditions the SAG will be operating in, it is possible that the actual operational window for the desired mission is actually less than 72 hours. As an example, SEA23 modeled an operational window of 24 hours with the resulting operational availabilities for the 45 and 90 node complements of 0.97 and 1.0, respectively, which does not change the outcomes appreciably. The cost of the 1.0 availability for a 24-hour mission is not worth the cost in capability by losing the manned helicopter. Based on this cost estimate and the operational availability of the two options, the recommendation is to equip each SAG with a 45 unit DP-5X Wasp and Link 16 combination. This will give the SAG commander an acceptable operational availability for the SOS while maintaining a manned helicopter asset to complete other missions.

IX. RECOMMENDED FUTURE ANALYSIS

SEA23 identified multiple areas during the project's research for recommended future exploration. Because of scoping and the assumptions, however, promising ideas and possible additional avenues for exploration were truncated or not addressed in the final solution. These form the basis for future analysis recommendations.

As distributed lethality continues to evolve and becomes an important and significant aspect of naval surface forces, the reliance and necessity for unmanned systems will continue to become readily important. Unmanned systems represent the next future force warfighting transition. Unmanned systems provide a relatively inexpensive and risk reduction approach towards conducting operations, particularly in A2AD environments. The following sections identify areas SEA23 saw as potential for additional research. The team identified these through the SE process and if more time were available, substantially greater insight into cross-domain solutions towards integrated fire control is possible.

A. GREATER INSIGHT INTO UNDERSEA DOMAIN

This project focused on surface and air technologies. SEA23 recommends that greater interaction occur with various undersea warfare stakeholders for input and integration of undersea components to the cross-domain architecture. Furthermore, engagement and involvement at the Submarine Technology Symposium (STS) might provide valuable insight into the interoperability of undersea-unmanned systems (http://www.jhuapl.edu/sts/Registration.aspx). Additional engagement will be beneficial with various stakeholders within the undersea warfare curriculum at NPS.

The U.S. Navy is executing a significant amount of effort to create an undersea network system of systems. Using this framework and architecture, integrated into the SEA23 capstone provides a significant way-ahead with the full-scale cross-domain effort. With the ability to communicate and relay information in the undersea realm and undersea environment, the overall scale of information relay grows substantially. Greater

investigation for the integration of the undersea domain with the surface/air domains shall provide significant operational capabilities for forward deployed forces (Eckstein 2016b).

In addition to exploring the wide range of possible avenues and platforms with undersea warfare, communication networks and communication relay paths provide a possible area for further research. Exploration and insight into the Acoustic-to-Radio Frequency linkage will be appropriate in relaying of above surface vs. below surface information. In particular, how does an undersea platform communicate and relay information to a surface or air platform? Investigation centered on the seamless transition in data relay between these domains will provide a significant enhancement to conducting operations in multiple domains. Two current projects fit this description: Tactical Undersea Network Architectures (TUNA) and Waveglider. TUNA seeks to provide an underwater fiber optic network with surface buoys acting as the subsurface to surface link (Klamp 2015). This will enable a long distance high bandwidth transmission line in the subsurface environment, which will be very difficult to detect except at the entry and exit buoys. Liquid Robotics, Incorporated is developing the robotic platform Waveglider. This system consists of an autonomous unmanned surface vehicle with a tethered acoustic package towed underneath. They have conducted extensive testing on this system and it provides a capability to relay undersea acoustic information to the surface or airborne platforms in the radio frequency spectrum (Liquid Robotics 2016).

B. ENHANCEMENTS TO EFFECTIVENESS OF SOS WITH FUTURE DATA LINKS

SEA23 examined only a few of the available data links based on interoperability and future interoperability with current naval platforms. Future integration and examination of data links might provide significant enhancements to the system of systems. With the ability for nodes to carry advanced systems, the overall structure of the system of systems gains greater operational effectiveness. Overall enhancements related to minimizing required power output, increasing UAV payload capacity, and decreasing data link hardware weight, such as increasing mission time, will enable the system of systems with the scenario to broaden and gain much greater levels of feasibility and capability.

C. ALTERING OR RE-ADJUSTING THE SCENARIO

SEA23 focused on capabilities and constraints of a three DDG SAG. Follow-on research can focus on the trade space related to AFP with the integration of other platforms (LCS, CG, LPD, etc.). Understanding the various tradeoffs associated with AFP will provide a much greater insight into the operational capabilities that can exist with an extremely modular and versatile system of systems. Additionally, through the analysis of various AFP, altering the scenario and imposing different assumptions on the problem statement will steer or scope the project differently. Altering, removing, or adjusting SEA23's assumptions in a follow-on research scenario might make the solution much more feasible or help identify areas for enhancements.

D. DARPA INJECTS

DARPA continues to lead the DOD on various innovative solutions for future operations. Increasing interaction and insight into DARPA projects will help feed into the various possibilities for future integration into the SEA23 system of systems. DARPA has developed numerous platforms, which could find use as forward-looking sensor platforms for integration. Greater interaction and integration of the DARPA projects are will occur during the course of their development.

E. GREATER JOINT INTEGRATION

This project is adaptable to a wide range of military operations. The predominant research and solution focused on rely of information in the maritime environment, but applications in other military domains exist. Each service has its own approach towards unmanned systems and unmanned systems integration. For example, integration of the USAF Broad Area Maritime Surveillance (BAMS) UAV will enable non-organic air assets to integrate into the organic system of systems to increase coverage, range, mission time, etc. A full-scale joint interoperability involving all services will seek to provide a fully networked and integrated solution for cross-domain operations.

For purposes of enhancing tactical offensive operations, future research can focus on the integration of the USAF Long Range Strike Bomber (LRS-B) to provide

significant levels of lethality. Using a stealth bomber and its offensive payloads will enhance naval strike capabilities by providing an avenue for integration between the system of systems and the LRS-B. "Smart weapon" systems integration

One item that repeatedly arose when addressing operating in a DDIL environment was in-flight missile feedback and the ability for missiles to receive updates and targeting information while in flight. A possible solution to this constraint investigates the ability for the system of systems to provide this level of information and detail. This will require greater fidelity and speed of information relay through the node platforms. Greater insight into the feedback loop or feedback chain of an inflight missile will greatly enhance naval lethality inside the scenario by providing much greater clarity and precision to weapons engagement.

F. PRECISION, NAVIGATION, AND TIMING (PNT)

SEA23 assumed degrading GPS capabilities, but not its complete loss or denial through the project. Identifying this assumption proved that reliance on GPS for PNT represents a highly complex adjustment to current operations. The reliance on GPS for almost all military operations is a key vulnerability, particularly when operating in a DDIL environment. There are a variety of measures that can be implemented in overcoming this issue (Fixed triangulation for positioning, celestial navigation); however, the speed, accuracy, and ease of using GPS must be explored and augmented by possible other systems. The current backup to GPS is INS, which is accurate; however, requires weekly updates to ensure accuracy. For purposes of providing sensors and weapons with pinpoint accuracy, greater exploration needs to occur in overcoming this challenge and providing a solution for minimizing the reliance on GPS.

G. QUICK-LAUNCH "CUBE-SATELLITES"

Based on the assumption that reliance on satellites will be severely degraded, the idea of using Cube-Satellites provided an alternative means in this denied environment. The idea involved launching a satellite via the vertical launch system (VLS) on a ship or submarine. This will seek to provide sustained satellite operations in a contested environment to support operations. Providing this localized satellite coverage will assist

in overcoming the issues associated with PNT. Furthermore, localized satellite capabilities decrease the reliance on UAV platforms. Research can focus on the feasibility of Cube-Satellites and the potential EM vulnerabilities associated with operations. The focus can be aimed at overcoming the PNT issues, while simultaneously providing forward operating forces with the ability to update positioning information for possible offensive engagements (such as updating operating INS).

H. CONVERSION OF CURRENT MANNED SYSTEMS TO UNMANNED SYSTEMS

To provide increased levels of platform speed and capability, research can focus on utilizing the current force structure platforms and converting these to unmanned systems to operate in the DDIL environment. For example, the proposal to convert "moth-balled" aircraft (from the aircraft boneyard) into unmanned systems to provide additional coverage and greater levels of speed and range. Furthermore, conversion of C2 platforms (E-2D Hawkeye) into unmanned systems will provide decreased risk to manned assets, while providing the current capabilities that are available to operating forces. Research exploration can focus on the full-scale cost effectiveness and cost analysis associated with system conversion and the applicability of these operating systems.

I. DISPOSABLE OR NON-RECOVERABLE OPTIONS

This project focused on organic, recoverable systems. Future analysis should ask if this is necessary or if a disposable, non-recoverable system will suffice. Research exploration can focus on the cost effectiveness of disposable systems and explore the various trade space associated with disposable systems. For example, if these disposable systems acted like sonobuoys, can they provide enhanced capabilities or will the structure of the force be limited to the duration of these operating systems? Future research will provide additional avenues into numerous possibilities for enhancing the solution and providing a more feasible approach. SEA23 focused on only a handful of current available platforms and systems; however, further exploration of additional commercial off-the-shelf or government off-the-shelf platforms might provide greater or enhanced

effectiveness. One possibility is the use of solar-powered UAVs that has Link-16 capability. This would fulfill a long-range, long dwell time capability that current small rotary UAVs lack.

J. NON REAL-TIME OPTIONS

Difficult coverage areas prompt further research into non real-time options, as when a node detects a possible target, but does not have another relay node in range. The node will store its information, move to within line-of-sight of another node, and then transmit its information. While the real time capability will be lost in this scenario, this capability will ensure that the information itself is not lost. This requires research into storage capacity and modifications to the networks themselves. However, the project team thinks that this will be a worthwhile addition to the system of systems.

APPENDIX A: SEA23 TASKING STATEMENT

NAVAL
POSTGRADUATE
SCHOOL

17 JUL 2015

Memorandum for Systems Engineering Analysis Cohort 23 (SEA23)

Subj: FY2016 SEA23 Capstone Projects: Tasking and Timelines

Enclosures:

Tab A: Future Unmanned Systems to link cross-domain fires
Tab B: Proposal for Coordinated Naval Postgraduate School Cross-Campus Project Creating
Tab C: IRB Student Checklist

1. This memorandum provides the FY2016 guidance for the conduct of the Systems Engineering Analysis (SEA) integrated project, which is required as partial fulfillment for the SEA degree. SEA students will deliver completed project reports and final briefing materials to faculty advisors in accordance with the following plan and milestones. Each group will:

    a. SEA23 develop project proposals and management plans during the Fall Quarter AY2016. These proposals and plans will serve to focus initial research and analysis. These plans will be reviewed and updated frequently as research progresses.
    b. Conduct project reviews approximately every six weeks, finishing with a final brief to interested stakeholders on and off campus.
    c. Assign a report lead from your team. Work closely with faculty advisors to prepare the final reports for faculty advisor signature by 4 work-weeks before graduation. The final reports are then due to the SEA chairman one week later; and to the Operations Research and Systems Engineering department chairmen one week before graduation.

2. SEA students are expected to identify and integrate students and faculty from across the campus – and also from outside NPS – to participate directly in the project or to provide source documents, technical knowledge and insights, and knowledge of evolving requirements, capabilities, and systems. This participation could include students who would join project groups; students doing related individual thesis topics from TSSE, TDSI, OR, IS or SE; faculty inside or outside NPS who have expertise related to the project; and appropriately engaged government agencies and industry developers. It is the students' responsibility to integrate the efforts of outside participants in the projects. Faculty advisors and the SEA Chair will, of course, significantly assist in these efforts.

3. Prior to commencing the formalized systems engineering and analysis process including stakeholder analysis, the SEA team will consult with Dr. Larry Shattuck, Chairman of the NPS Institutional Review Board and submit to him TAB A, a

general description of the team's systems and analytical approach to address the tasking, a completed IRB student research form (Tab C) and a list of candidate questions for stakeholders to review. The intent is to ensure questions are oriented about the "what" of the systems and not about the "who" of the stakeholder.

4. The analysis will employ the systems engineering and operations research methodologies presented in class work and from the project advisors. The role of the SEA students is that of the lead project systems engineering team, working closely with other members of the project engineering teams from TDSI and other campus curricula. SEA students will be expected to define the functions and performance of systems, develop alternative architectures to meet those functions, and evaluate the alternative architectures for performance and cost. In executing these tasks, students will be defining and understanding the overall project requirements, recognizing that the definition process is iterative and will evolve as the project progresses.

5. Grades are assigned to the participants in these projects. Although work is performed as part of a team, individual performance will be the basis for this evaluation. Successful completion and documentation of the project is a degree requirement.

6. The SEA23 project will build on, possibly challenge, but not replicate, other DOD and SEA projects. SEA23 will examine unmanned systems' potential contributions to establish cross domain and integrated naval fires in contested environments. Their work will build upon and expand work started by SEA21A, maritime ISR to support surface to surface engagements. SEA23 will coordinate their study efforts, participate and occupy leadership roles in other FY15/16 efforts at NPS aimed at creating asymmetric advantages in warfighting. These activities, coordinated by the Chair of Systems Engineering Analysis and Chair Warfare innovation, are described in Tab B.

Jeffrey E. Kline
Chairman, Systems Engineering Analysis Curriculum
Professor of Practice, Operations Research
Naval Postgraduate School
Monterey, CA 93908

Distribution: SEA23 students; Profs. Hughes, Jacobs, Giachetti, Whitcomb, Langford, Chung, Stevens, Solitario, Kline, Harney, Papoulias, Porter, Boger, Brutzman, Buettner, President Route; Provost Hensler; Deans Wirtz, Durkee, McCormick, Paduan, and Moses, CAPT Daniel Verheul; Dr. Shattuck; CAPT Jeff Hyink; CDR Aparicio, LCDR Littrell, Dr. Anthony Pollman, RDML Williams, RADM Ellis, RADM Breckenridge (OPNAV N9I), Mr. Mike Novak (OPNAV N9IB), Mr. Chuck Werchado (N81B), Mr. Bill Glenney (SSG), and Ms. Kathie Cain

TAB A

SEA 23 Tasking
Unmanned Systems in integrating cross domain naval fires.

"Design a fleet system of systems and concept of operations for employment of a cost effective and resilient unmanned and manned system capable of allowing cross domain targeting information in a contested area in the 2025-2030 timeframe. Consider manned and unmanned systems in all domains to provide sufficient information to support effective tactical offensive operations by air, surface, undersea and cyber. Explore how unmanned systems may contribute to cross-domain information exchange to support navy fires or to create an "all domain" naval integrated fire control capability to create an asymmetric warfighting advantage in a contested environment. Explore alternatives in adaptive self-governing communications networks from T1-like capability to a "thin-line" getting the target coordinates through capacity. Consider employment requirements, operating areas, bandwidth and connectivity, interoperability, sensor data processing, transfer and accessibility, logistics, forward arming and refueling (FARPS) basing support in forward areas or from CONUS bases and joint contributions. Generate system requirements for platforms, sensors, and communications in a challenging EM environment. Develop alternative architectures for platforms, sensors, manning, command and control, intelligence collection/dissemination and consumption, communication and network connectivity, and operational procedures. Address the costs and effectiveness of your alternatives in mission areas like at-sea strike and electronic maneuver warfare."

Advisors:
Dr. Fotis Papoulias, Systems Engineering Department
Dr. Michael Atkinson, Operations Research Department

On Campus Subject Matter Experts:
CAPT Jeff Hyink, USN for Naval Fires background
Dr. Ray Buettner, Director CRUSER
Dr. Alex Bordetsky IS Department
RDML Rick Williams, USN (Ret), Mine and Expeditionary Warfare Chair
RADM Jerry Ellis, USN (Ret), Undersea Warfare Chair
CAPT Daniel Verheul, USN, Senior NPS Intelligence Officer
Professor Wayne Hughes, CAPT, USN (Ret), Operations Research Department
Professor Jeff Kline, CAPT, USN (Ret), Operations Research Department
LCDR Brian Judy, USN SEA 21 Graduate

Off Campus Points of Contact:
OPNAV N9I Mr. Mike Novak (Sponsor)
OPNAV N99 TBD
COMPACFLT N9 Mr. David Yoshihara

TAB B

NPS Warfare Innovation Continuum
A Coordinated Naval Postgraduate School Cross-Campus Project FY15-16
"Creating Asymmetric Warfighting Advantages"

Purpose: Coordinate and execute a series of cross-campus educational and research activities synchronized by the Chair of Systems Engineering Analysis and the Chair of Warfare Innovation with a central theme of exploring the creation of asymmetric warfighting advantages across all domains. Focus will be on leveraging unmanned systems to enhance cross domain operations and developing the Electromagnetic Maneuver Warfare (EMW) concept by extending research in electronic warfare, spectrum management, assured C2, and integrating planning and fires.

Background: Emerging technologies in unmanned systems; autonomy; missile systems; undersea systems; long-range, netted and multi-domain sensors; and networks create a new environment for operations on and over the sea. This changing technology environment both challenges traditional fleet operations and provides opportunities for innovative tactics, techniques, and procedures to achieve naval objectives in sea control, power projection and counter Anti-Access Area Denial (A2AD) strategies. This paper proposes a series of independent, but coordinated cross-campus educational and research activities to provide insight into the opportunities for warfighting in the complex and electromagnetically contested environment at sea and near the sea-land interface. It will address opportunities in unmanned systems technologies to support integrated fires and tactically offensive operations, and further develop the concept of electromagnetic maneuver warfare as an asymmetric advantage. The larger research question is **"Will emergent technologies innovatively employed provide asymmetric warfighting advantages in contested environments?"**

.

APPENDIX B: INSTITUTIONAL REVIEW BOARD QUESTIONS

Institutional Review Board (IRB) Questions for SEA-23 Project

Overview: The following set of questions highlight a large percentage of the types of questions that will be asked and addressed through the research for the SEA-23 CAPSTONE project. This set of questions will be used as a baseline for conducting research with potential stakeholders in seeking a solution for the prescribed problem statement. Each question has been derived through a breakdown and understanding of the problem statement. Further questions may arise as the problem statement continues to evolve.

Mission (Tasks):

1. Define the scale of "supporting effective tactical offensive operations" in the realm of Air/Surface/Undersea/Cyber.
   a. What types of offensive operations?
2. Are there specific Mission Essential Task Lists (METL) items for this scenario for cross-domain operations?
   a. What are the prioritization levels of these METL's?
   b. Who are the primary stakeholders that would define the most significant METL's?
   c. Are there METL's that we should seek to focus on for offensive operations?
3. What is the expectation of effective tactical offensive operations?
   a. Kinetic attack?
   b. Denial of assets?
   c. Deterrence?
   d. Freedom of Navigation (FON)?
   e. Maritime/Air Supremacy & Superiority?

Anti-Access/Area Denial (A2/AD) / Scenario:

1. Given a denied Anti-Access/Area Denial (A2/AD) environment, what are the current challenges from the perspective of US (joint) operations?
2. How is the adversary (scenario) planning their A2/AD environment and what are they doing to counter the current US operations, abilities, and capabilities?
   a. How do they see the US as a threat?
   b. What vulnerabilities are they exploiting?
3. What capabilities do the US Air Force, US Army, US Navy, and US Marine Corps currently have to counter A2/AD and how do we use all of these assets in a denied environment through joint interoperability?
4. What are the types of weapons the US will employ in an A2AD environment?
   a. Are there weapons currently being fielded?
   b. Are there specific technological requirements for these weapons?
   c. What are the characteristics of these weapons and their intended uses (i.e. anti-surface cruise missiles / anti-air weapons, etc.)?
   d. What are the ranges and maneuverability and detectability of these weapons?
5. What types of weapons will adversaries employ in the South China Sea?
   a. What are the priority levels of threats?
   b. What is the US doing to counter these threats / potential threats?

Cross-Domain Operations:

1. What are the existing technologies used for cross-domain operations?
2. What are some challenges to incorporate cross-domain communications and fires?
3. What unmanned systems are currently available for incorporation into the scenario?
    a. Which unmanned systems would be best used in an A2/AD environment to both support and augment US forces operating in this arena?
4. What current capabilities do unmanned systems provide in operating in a denied environment? How does [insert company/organization name] approach cross-domain operations?
    a. Addressing the challenges/constraints listed above, how does the respective [company/organization name] incorporate and adapt to these challenges?
    b. What technology is capable of operating in a denied environment?
    c. Are these manned or unmanned systems?
5. What challenges have [insert company/organization name] encountered in cross-domain operations?
    a. Particularly from the perspective of joint interoperability
    b. Particularly from the perspective of operating in a denied (A2/AD) environment.
6. What requirements would [insert company/organization name] place on a system operating in the cross-domain contested environment?
    a. Do these requirements align with the requirements that we have been given for this project?
    b. Should additional requirements be added to help scope-down our project?
    c. How are these requirements prioritized?
        i. What are the Key Performance Parameter (KPP) requirements (aka the "non-negotiables")?
7. What current Navy/Joint systems support Integrated Fire Control (IFC) operations?
    a. Cooperative Engagement Capability (CEC)?
    b. Navy Integrated Fire Control – Counter Air (NIFC-CA)?

Unmanned Systems (UxV):

1. What is the public perception of unmanned vehicles deployment in foreign countries by the US military?
    a. Are there political constraints?
    b. Are there legal constraints?
    c. What are possible ethical concerns for unmanned operations and how would DoD address them? (What organization is responsible for addressing the doctrine / ROE for unmanned systems?)
2. What hurdles would be expected to overcome for UxV operations?
3. What is the expected endurance time for UxV in the next 15 years?
    a. What is the plan for recharging or recovering these UxV's?
    b. How many UxV's can operate at any given time to effectively provide sensor coverage over a large area?
    c. What implementations are made to prevent an adversary from gaining access or disturbing these operating systems?
        i. Compromising operations by hacking into / stealing / destroying, etc.
4. What are the challenges in communication with a network of underwater sensors? How is bandwidth to be controlled if there are multiple UxV's in use at one time in the same network?

5. How will UxV maintain comms with other platforms in EMCON status?
    a. What are the affiliated challenges?
    b. What is the way-around?
6. What will UxV range be in 10 years?
    a. All domains (Air/Surface/Sub-surface)
7. What capabilities will the UxV have in terms of communicating with other platforms besides submarines?
8. What other uses are currently being fielded for multiple mission UxV platforms (besides surveillance/sensors)?
    a. EM environment (jamming)?
    b. Long-range communications extension?
    c. Weapons delivery?
9. What is the envisaged extend of unmanned vehicle deployment (air, land and sea) for US military operations?
    a. Do they replace manned systems or complement them?
10. What are the challenges experienced by ground operators when dealing with manned and unmanned systems?

Technology:

1. What sensors are currently available for incorporation into the scenario? Are these sensors capable of operating in a denied environment? How is the information that these sensors obtain relayed to the appropriate decision and interpretation source?
    a. Once information is gathered by a sensor, what is the network path for delivery?
    b. Are there prioritization levels available for timely processing and dissemination of potentially hostile or time relevant information?
2. Are we seeking to strictly use existing capabilities and repurposing AND/OR develop an entirely new system?
    a. Is there a system currently being fielded that supports interoperability in a denied environment? Can we use that system as a template/model for our future defined system? (For example: Does our prospective system mimic other systems such as NIFC-CA or other Integrated Fire Control (IFC) related systems?)
3. Will the US Navy have technology that will be capable of passing large amounts of data through the water that will have the speed of kbps, or mbps, not the current bps?
4. What are the considerations to develop the next generation of C4ISR network centric architecture to support cross-domain operations?

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C: FUNCTIONAL DECOMPOSITION

T.1.1 “To Launch”: The function of ‘to launch’ provides the system with the ability to move the unmanned platform from its transit ship into the air, sea surface, or sea sub-surface.

T.1.1.1 “To Check Weather”: Weather conditions must be less than the maximum launch threshold for the unmanned platform.

T.1.1.1.1 “To Call Weather Service”: A weather-monitoring agency or office continuously updates current and future weather conditions.

T.1.1.1.2 “To Decide Go/No Go”: The crew decides whether the weather supports launching the unmanned vehicle or if the mission must be delayed or cancelled due to, weather conditions exceeding the maximum launch threshold.

T.1.1.2 “To Use Launch Equipment”: The launch equipment is the physical object(s) used to move the unmanned vehicle from its transit ship into the air, sea surface, or sea sub-surface.

T.1.1.2.1 “To Perform PCC/PCI on Launch Equipment”: The crew checks the equipment for indications that it will not perform its primary function of launching the unmanned vehicle, prior to the unmanned vehicle’s launch.

T.1.1.2.2 “To Store Launch Equipment”: The launch equipment must be stored while not in use.

T.1.1.2.3 “To Set-up Launch Equipment”: The crew places the launch equipment in an operational state prior to launching an unmanned vehicle.

T.1.2 “To Deploy”: The function of ‘to deploy’ provides the system with the ability to sustain, support, and transport unmanned platforms while in transit to and within the area of operations.

T.1.2.1 “To Prepare”: The crew readies the unmanned system for use by considering the maintenance, preflight checks, and upload mission data.

T.1.2.1.1 “To Maintain”: The maintainability and availability of the unmanned systems.

T.1.2.1.1.1 “To Conduct Maintenance”: Identifying and correcting issues with unmanned systems and their associated equipment.

T.1.2.1.1.2 “To Keep Available”: The probability that unmanned systems will operate satisfactorily when called upon (Blanchard and Fabrycky 2011, 441).

T.1.2.1.2 “To Conduct PCC/PCI”: The pre-flight checks that will identify any potential issues with the unmanned systems and their associated equipment.

T.1.2.1.3 “To Upload Data”: The unmanned system must understand its operating parameters for the mission it will perform. The crew uploads mission data into the unmanned system’s control system.

T.1.2.1.3.1 “To Know Mission Plan”: The unmanned system must have information regarding its route and loitering time.

T.1.2.1.3.2 “To Know Threats in Vicinity”: The unmanned system must identify threats nearby.

T.1.2.1.3.3 “To Know What Data to Relay”: The unmanned system must have data encryption keys so that it knows whether a communication signal is authentic or not.

T.1.2.1.3.4 “To Know Team Configuration”: The unmanned system must know where receiving nodes are spatially located in relation to its location for successful data transmission.

T.1.2.2 “To Store”: The unmanned systems and their associated support equipment must be safely stored when not in use.

T.1.2.2.1 “To Keep Safe”: The unmanned systems must be kept safe to avoid damage or compromise.

T.1.2.2.2 “To Secure”: The unmanned systems must not be damaged while in storage.

T.1.2.2.3 “To Encrypt”: The unmanned systems must be secure from an adversary’s attempt to gain access to stored data.

T.1.3 “To Operate”: The function of ‘to operate’ provides the system with the ability to perform its mission of communications relay from sensor to C2 and back to sensor.

T.1.3.1 “To Navigate”: The unmanned systems must be able to know where it is located within the operational area and move to its area of operations from its launch point.

T.1.3.1.1 “To Know Current Location”: The unmanned system’s ability to know its current location is necessary for it to navigate to its final loitering area of operation.

T.1.3.1.1.1 “To Use Stars”: Celestial navigation is the use of the sun and stars to locate position. Mariners have used it for centuries (Celestial Navigation.net 2014)

T.1.3.1.1.2 “To Use Triangulation”: Using the distance between two or more nodes in order to form a triangle and establish a nodes relative position to those points (Webster’s Dictionary 2016).

T.1.3.1.1.3 “To Use a Map”: Software aboard unmanned platform will use relativity in relation to other platforms to distinguish positioning

T.1.3.1.1.4 “To Recognize Terrain/Landmarks”: Associating terrain and land features with prior understanding of what the terrain and landmarks are supposed to be.

T.1.3.1.1.5 “To Use Planets”: Unmanned system can use celestial bodies to navigate.

T.1.3.1.1.6 “To Use Earth’s Magnetic Field”: Using the naturally occurring magnetic fields found on Earth to navigate.

T.1.3.1.1.7 “To Use Echolocation”: Using reflected sound to determine location and navigate to waypoints.

T.1.3.1.1.8 “To Use Dead Reckoning”: Use a predetermined trajectory, speed, and time to move through waypoints.

T.1.3.1.2 “To Move to a New Waypoint”: The ability to fly, float, walk to a predetermined position.

T.1.3.1.2.1 “To Fly”: To move in or pass through the air using wings (Webster’s Dictionary 2016)

T.1.3.1.2.2 “To Float”: Rest on the surface of or be suspended in a fluid (Webster’s Dictionary 2016)

T.1.3.1.2.3 “To Walk”: To move with your legs at a speed that is slower than running (Webster’s Dictionary 2016).

T.1.3.2 “To Relay Communication”: The relay of information consists of three steps: data reception, data processing, and data transmission.

T.1.3.2.1 “To Transmit Data”: Communications data moves to another node using electromagnetic waves. The changing of the input signal as preparation for transmission, by adjusting the format of the waveform as required. The increase in the waveform signal strength as necessary and determined by losses in transmission medium. Propagate the prepared signal in the necessary medium by specific waveform (Harney 2013).

T.1.3.2.2 “To Process Data”: The node receives communications data, which, after confirmation, becomes transmission data sent to a receiving node. Change of signal into an adequate waveform for transmission in medium. Determine errors in signal. Arrange data for specific encoding for transmission. Ex: on-off keying. Prepare input signal for transmission as output information/signal. Determining the data signal to time, phase, and channel (frequency). (Harney 2013)

T.1.3.2.2.1 “To Turn Received Data into Transmit Data”: The process of receiving communication data and turning the data into a transmittable waveform.

T.1.3.2.2.2 “To Confirm Message Source”: The message can be deception signal sent by an adversary. In order to prevent transmission of erroneous or deceptive messages from, it is necessary to confirm the source of the message.

T.1.3.2.2.3 “To Determine Where the Message is Going”: The message requires a destination prior to sending it.

T.1.3.2.3 “To Receive Data”: The platform collects the data (specific signal frequency(ies)) that it uses or must re-transmit through a specified communication network (Harney 2013).

T.1.3.2.3.1 “To Use Receive Antenna”: A receive antenna is necessary to collect the electromagnetic waves containing the communication data.

T.1.3.2.3.2 “To Receive Noise”: Noise is erroneous electromagnetic interference that may be present in the atmosphere or node systems.

T.1.3.3 “To Protect”: The unmanned systems must be kept safe from harm or loss by ensuring their flight altitude, airspeed, and loitering time falls within threshold values.

T.1.3.3.1 “To Determine Flight Altitude”: The altitude at which a UAV must fly at according to mission parameters.

T.1.3.3.2 “To Determine Airspeed”: The speed at which a UAV must fly at according to mission parameters.

T.1.3.3.3 “To Determine Loitering Time”: The length of time an unmanned system can operate before power levels drop below a threshold and the unmanned system will fails prior to retrieval.

T.1.4 “To Recover”: The function of ‘to recover’ provides the system with the ability to retrieve the unmanned platforms after mission completion.

T.1.4.1 “To Check Suitability for Recovery”: The suitability of recovery for the unmanned system based on the status of the unmanned system and the weather.

T.1.4.1.1 “To Check Remote Vehicle Status”: The status of the unmanned system is critical to its recoverability. It must be able to make it to its recovery point under its own power.

T.1.4.1.2 “To Check Weather Conditions”: Weather conditions must meet or exceed the recovery threshold for the unmanned platform.

T.1.4.2 “To Use Recovery System”: A recovery system is necessary for the successful retrieval of the unmanned system. It must be set-up when the unmanned

systems are in use and stored while they are not in use. It must be reliable so that the recovery system can perform its main function.

T.1.4.2.1 “To Perform PCC/PCI on Recovery Equipment”: The pre-flight checks that will identify any potential issues with the recovery system.

T.1.4.2.2 “To Store Recovery Equipment”: The recovery equipment must be stored while the unmanned system is not in operation.

T.1.4.2.3 “To Set-up Recovery System”: The recovery equipment must be set-up before any recovery operations can occur.

T.1.4.3 “To Acquire and Track Remote Vehicle”: The retrieving system must be able to know the status and location of the unmanned system.

T.1.4.3.1 “To Correct Remote Vehicle”: The retrieving system needs to ensure the unmanned system is aware of the retrieving system’s ability to recover the unmanned system.

T.1.4.3.1.1 “To Give Final Clearance for Recovery”: The unmanned system needs to know if the retrieving system is ready to recover the unmanned system. The retrieving system notifies the unmanned system that it is ready for its recovery.

T.1.4.3.1.2 “To Abort and Re-attempt Recovery”: The unmanned system must be able to abort the recovery operation and re-attempt when the retrieval equipment is ready to recover the unmanned system.

APPENDIX D: CRITICAL OPERATIONAL ISSUES, MEASURES OF EFFECTIVENESS, MEASURES OF PERFORMANCE, AND DATA REQUIREMENTS

- COI 1: Will the system of systems be an effective information relay?
- MOE 1.1: Minimize relay time within the node platform
- MOP 1.1.1: Time for input/output of relay signal shall be less than GOTS specification.
- DR 1.1.1: Measure delay time signal transfer
- MOP 1.1.2: Maintain zero processing on data transferring nodes
- MOE 1.2: Communicate line-of-sight (LOS) between nodes
- MOP 1.2.1: LOS range based on signal power
- DR 1.2.1.1: Measure required power output (Watts)
- MOP 1.2.2: LOS range based on altitude
- DR 1.2.2.1: Determine optimal operating altitude
- DR 1.2.2.2: Determine minimum operating altitude
- MOP 1.2.3: LOS range based on environmental conditions
- DR 1.2.3.1: Determine atmospheric attenuation at operating frequency
- DR 1.2.3.2: Determine cloud coverage
- MOE 1.3: Area of Communication Relay Coverage
- MOP 1.3.1: Footprint of battlespace no less than 500 NM in radius
- DR 1.3.1.1: Measure transmission power level for adequate coverage within communication area
- MOE 1.4: Operate using effective Tactical Data link/network
- MOP 1.4.1: Link/Network to relay sensor data to prosecuting platform
- DR 1.4.1.1: Measure data rate
- DR 1.4.1.2: Measure required bandwidth

- DR 1.4.1.3: Measure network latency
- DR 1.4.14: Measure Link Margin
- MOP 1.4.2: Maintain Information Assurance
- DR 1.4.2.1: Determine mode of encryption.
- DR 1.4.2.2: Determine mode of user authentication
- MOP 1.4.3: Maintain Anti-jam / jam resistant properties
- DR 1.4.3.1 Determine susceptibility to jamming.
- MOP 1.4.4: Suitable physical requirements
- DR 1.4.4.1: Equipment weight/size/power requirements
- DR 1.4.4.2: Compatibility with platforms
- MOE 1.5: Data Reliability
- MOP 1.5.1: Network supports topology requirements
- DR 1.5.1.1: Minimum number of nodes required for information relay
- DR 1.5.1.2: Measure of network resilience
- MOP 1.5.2: Minimize bit error rate
- COI 2: What defines the system-of-systems availability?
- MOE 2.1: Maintainability
- MOP 2.1.1: Maintain a minimal mean corrective maintenance time
- DR 2.1.1.1: Airframe repair time for specific faults
- DR 2.1.1.2: Propulsion replacement time
- DR 2.1.1.3: Sensor replacement time
- DR 2.1.1.4: Communication suite replacement time
- DR 2.1.1.5: Mean preventive maintenance time
- MOP 2.1.2: Maintain a minimal mean operational mission failure repair time
- DR 2.1.2.1 Total hours of corrective time to restore failed nodes to mission capable status after an operational mission failure

- DR 2.1.2.2: Total number of operational mission failures
- MOP 2.1.3: Maintain a minimal mean time to repair
- DR 2.1.3.1 Sum total of corrective maintenance time
- DR 2.1.3.2 Total number of corrective maintenance actions
- MOP 2.1.4: Maintain a minimal mean time to restore node functionality
- MOE 2.2: Operational Availability
- MOP 2.2.1: Meets or exceeds desired operational availability.
- MOE 2.3: Maneuverability
- MOP 2.3.1: Speed
- DR 2.3.1.1: Max speed
- DR 2.3.1.2: Average speed given operational scenario
- DR 2.3.1.3: Max climb speed to required altitudes
- MOP 2.3.2: Altitude
- DR 2.3.2.1: Max altitude before performance degradation
- MOP 2.3.3: Range
- DR 2.3.3.1: Maximum operational radius on single load of power
- DR 2.3.3.2: Mean operational radius of different sensor load
- MOP 2.3.4: Endurance
- MOP 2.3.5: Station Keeping
- MOE 2.4: Reliability [duration of failure free performance on mission]
- MOP 2.4.1: Minimum number of nodes required to maintain physical network
- MOP 2.4.2: Mean time for nodes to conduct self-patching of mesh network in event of particular nodes losing signal
- MOP 2.4.3 Mean time between operational mission failure
- DR: Operating time

- DR: Number of operational mission failures
- MOP 2.4.4: Operation in foul weather
- COI 3: What are the system of system's capabilities for interoperability?
- MOE 3.1: Is the system capable of interoperating with proposed network of systems
- MOP 3.1.1: Network must be fully interoperable with existing C2 systems
- MOP 3.1.2: Network must maintain a maximum sustainable throughput equal to existing C2 systems
- DR 3.1.2.1: What is the system bit error rate at maximum operating range?
- DR 3.1.2.2: What is the system bit error rate at nominal operating range?
- DR 3.1.2.3: What is the degradation level in moderate to adverse weather conditions?
- COI 4: Will the system of systems be survivable in operations?
- MOE 4.1: Is the UAV survivable?
- MOP 4.1.1. What are the probabilities of detection and tracking of the UAV in the Area of Operations?
- MOP 4.1.2. What is the probability of kill given a hit?
- MOE 4.2: Is the UAV Vulnerable
- MOP 4.2.1 Is the UAV capable of operating with damage?
- MOP 4.2.2. What is the probability of mission completion given damage?
- MOE 4.3 Is the UAV Susceptible
- MOP 4.3.1 What is the level of probability of detect of the UAV?
- MOP 4.3.2. What is the level of probability of tracking the UAV?

Launch Operation

- COI 5: Is the UAV rapidly deployable?

- MOE 5.1: Deployment time
- MOP 5.1.1: Time to setup unmanned vehicle for launch
- MOE 5.2: Initialization time
- COI 6: Is the UAV prepared for launch?
- MOE 6.1: Pre-flight
- MOP 6.1.1: Time to initialize unmanned vehicle for launch
- MOP 6.1.2: Time to initialize GPS/INS?
- MOP 6.1.3: Time to synchronize communication with terminal platform
- MOP 6.1.4: Attain minimum engine RPM before launch
- MOP 6.1.5: Achieve the required deflection on rudder, aileron and flap
- MOE 6.2: Environmental conditions for launch
- MOP 6.2.1: Maximum allowable wind speed for launch
- MOP 6.2.3: Maximum allowable sea state for launch
- COI 7: Can a sufficient number of UAV be launched as a sortie?
- MOE 7.1: Successful takeoff
- MOP 7.1.2: Number of successful takeoffs within specified time frame

Recovery Operation

- COI 8: Is the UAV able to execute its recovery (landing) procedures upon mission completion?
- MOE 8.1: Navigate to recovery site
- MOP 8.1.1: Time to reach to recovery site
- MOP 8.1.2: Number of recovery waypoint attain
- COI 9: Can the UAV be recovered with minimum resources?
- MOE 9.1: Landing space requirement
- MOP 9.1.1: Minimum landing space on recovery site
- MOP 9.1.2: Maximum levelness required on recovery site

- MOP 9.1.3 Terrain inclination/features
- MOE 9.2: Manpower requirement
- MOP 9.2.1: Minimum manpower to recover UAV
- MOP 9.2.2: Minimum skill level required for recovery operation
- COI 10: Can the UAV be recovered safely within minimum requirements?
- MOE 10.1: Safety considerations
- MOP 10.1.1: Minimum safety distance for personnel at recovery site
- COI 11: Can the UAVs be recovered in a reasonable time period?
- MOE 11.1: Successful recovery
- MOP 11.1.1: Number of successful recovery within specified period.
- COI 12: Is the system of systems transportable?
- MOE 12.1: Is the UAV capable of storage on a SAG ship (Packaging Requirements)
- MOP 12.1.1 Size of dismantled UAV
- DR 12.1.1.1 Determine dimensions (Length x Breadth x Height) of each UAV subsystem
- DR 12.2.1.1 Determine volume of storage compartment for all the containers
- DR 12.2.1.2 Determine the volume of space for storage of test equipment
- MOP 12.1.2 Size of assembled UAV
- DR 12.1.2.1: Determine overall dimension of UAV
- MOP 12.1.3: Size of support elements
- DR 12.1.3.1 Determine dimensions (Length x Breadth x Height) of each box
- DR 12.1.3.2 Total volume of all containers
- DR 12.1.3.3 Determine dimensions of structure to hold the UAV for assembly/dismantling/maintenance

- MOP 12.1.4 Weight of dismantled UAV
- DR 12.1.1.4.1 Determine weight of each UAV subsystem
- MOP 12.1.5 Weight of assembled UAV
- DR 12.1.5.1: Determine overall weight of UAV
- MOP 12.1.6: Size of support elements
- DR 12.1.6.1 Determine weight of each box
- DR 12.1.6.2 Total weight of all containers
- DR 12.1.6.3 Determine weight of structure to hold the UAV for assembly/dismantling/maintenance
- MOP 12.1.7 Sensitive equipment / costly equipment / classified equipment
- DR 12.1.7.1 Sensitive equipment / costly equipment / classified equipment

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Aerovironment. 2015. “DDL: Digital Data Link.” Accessed April 24. http://www.avinc.com/downloads/DDL_Datasheet_Revision_Final_v1.3.pdf.

Akers, Daniel, ed. 2014. *Understanding Voice and Data Link Networking: Northrop Grumman’s Guide to Secure Tactical Data Links*. San Diego: Northrop Grumman Corporation.

APL Team. 1995. “The Cooperative Engagement Capability.” *John Hopkins APL Technical Digest* 16, Number 4: 377–396.

Benson, Stephen, Alex Bordetsky and Wayne Hughes. 2016. “Mesh Networks in Littoral Operations.” USNI Blog. Accessed May 4. https://blog.usni.org/2016/05/12/mesh-networks-in-littoral-operations.

Bergesen, Sean A. 1993. “Adaptive Joint Force Packaging (AJFP): A critical analysis.” Master’s thesis. Naval Postgraduate School.

Blanchard, Benjamin S., and Wolter J. Fabrycky. 2010. *Systems Engineering and Analysis. 5th ed*. Upper Saddle River, New Jersey: Pearson Education.

———. 2011. *Systems Engineering and Analysis. 5th international ed*. Upper Saddle River, NJ: Prentice Hall.

Boehm, Barry. 2000. “Spiral Development: Experience, Principles, and Refinements.” Paper presented at the Spiral Development Experience and Implementation Challenges Workshop, University of Southern California, Los Angeles, California, February 9–11.

Boger, Dan. 2015. “Agile EMCON.” Presentation at the Warfare Innovation Workshop, Monterey, California, September 21–24.

Boyle, Ashley. The U.S. and its UAVs: A Cost-Benefit Analysis. July 24, 2012. Accessed April 21. http://www.americansecurityproject.org/the-us-and-its-uavs-a-cost-benefit-analysis/.

Cahill, Joe. 2015. “Distributed Lethality Feedback Report.” Presented at the Naval Postgraduate School, Monterey, California, August 25.

Celestial Navigation.net. 2014. “History.” Accessed April 18. . http://celestialnavigation.net/history/.

Cobham. 2015. “Cobham Antenna Systems.” Accessed April 24. https://www.cobham.com/communications-and-connectivity/antenna-systems/microwave-antennas/tactical-communications-antennas-link16/tactical-communications-link16-antennas-brochure/.

Coffman, Mark. 2015. “EMW.” Presentation at the Warfare Innovation Workshop, Monterey, California, September 21–24.

Cranney, John. 2015. “DARPA CODE.” Presentation at the Warfare Innovation Workshop, Monterey, California, September 21–24.

CRUSER Warfare Innovation Workshop. 2015. “Creating Asymmetric Warfighting Advantages.” September 21–24. Monterey: Naval Postgraduate School.

Czarnecki, Jonathan, and K. Todd Chamberlain. 2013. “Graceful Degradation: A C2 Design Virtue for Our Times.” Paper presented at the 18th International Command and Control Research and Technology Symposium, Alexandria, Virginia, June 19–21.

Defense Acquisition University (DAU). 2013. “Defense Acquisition Guidebook.” Fort Belvoir, Virginia.

Department of Defense Chief Information Officer (DOD CIO). 2010. “DODAF Viewpoints and Models: Operational Viewpoint: OV-1: High Level Operational Concept Graphic.” Accessed February 2016. http://dodcio.defense.gov/Library/DoDArchitectureFramework/dodaf20_ov1.aspx.

———. 2010. “DODAF Viewpoints and Models: Operational Viewpoint: OV-5a: Operational Activity Decomposition Tree and OV-5b: Operational Activity Model.” Accessed February 2016. http://dodcio.defense.gov/Library/DoDArchitectureFramework/dodaf20_ov5ab.aspx.

Eagle, James. 2013. “Search & Detection Theory (OA3602) Lecture Notes.” Monterey: Naval Postgraduate School.

Department of Defense Instruction (DODINST) 4650.01 Revision 1. 2005. Policy and Procedures for Management and Use of the Electromagnetic Spectrum. Arlington County: Department of Defense.

Program Executive Office, Integrated Warfare Systems (PEO, IWS). 2013. “Cooperative Engagement Capability Selected Acquisition Report (SAR).” Washington, D.C.: Department of Defense.

Program Executive Office, Integrated Warfare Systems (PEO, IWS). 2015a. “Multifunctional Information distribution System (MIDS) Selected Acquisition Report (SAR).” Washington, D.C.: Department of Defense.

Program Executive Office, Integrated Warfare Systems (PEO, IWS). 2015b. "MQ-8 Fire Scout Unmanned Aircraft System Selected Acquisition Report (SAR)." Washington, D.C.: Department of Defense.

Dragonfly Pictures, Incorporated (DPI). 2014a. "DP-14 Hawk." Accessed April 24. http://www.dragonflypictures.com/products/unmanned-vehicles/dp-14-hawk/.

———. 2014b. "DP-5X Wasp." Accessed April 24. http://www.dragonflypictures.com/products/unmanned-vehicles/dp-5x-wasp/.

———. 2013. "DP-12 Seahorse DP-12 Seahorse Vertical Takeoff and Land (VTOL) Unmanned Aircraft System (UAS). Essington: DPI.

Eckstein, Megan. 2016a. "CNO Richardson: Navy Needs Distributed Force of Networked Ships, Subs to Counter A2/AD Threat." USNI News, March 11. https://news.usni.org/2016/03/11/cno-richardson-navy-needs-distributed-force-of-networked-ships-subs-to-counter-a2ad-threat.

———. 2016b. "Navy: Future Undersea Warfare Will Have Longer Reach, Operate With Network of Unmanned Vehicles." USNI News, March 24. Accessed April 26. https://news.usni.org/2016/03/24/navy-future-undersea-warfare-will-have-longer-reach-operate-with-network-of-unmanned-vehicles.

Forsberg, Kevin, and Harold Moors. 1992. "The Relationship of Systems Engineering to the Project Cycle." Engineering Management Journal Vol. 4, No. 3: 36–43.

Galambos, James. 2016. Cross-Domain Maritime Surveillance and Targeting (CDMaST) Read Ahead. Arlington County: Defense Advanced Research Projects Agency.

GAMS. 2016. "General Algebraic Modeling System." Accessed April 19. https://www.gams.com/.

Guide to the Systems Engineering Body of Knowledge (SEBoK). 2016. "Stakeholder Needs and Requirements." Last modified March 25. http://sebokwiki.org/wiki/Stakeholder_Needs_and_Requirements.

Hanna, David J. 2015. "SWARM UAV: Maintainability and Availability." SE3302: System Suitability Project Report #2, Monterey.

Harney, Robert C. 2000. "The Enemy's Access Denial System: Potential Competitor Exploitation of U.S. Military Vulnerabilities." Monterey: Institute for Joint Warfare Analysis/Naval Postgraduate School.

———. 2013. *Combat Systems Engineering*. Monterey: Naval Postgraduate School.

Hayter, Anthony J. 2013. *Probability and Statistics for Engineers and Scientists, 4th Edition*. Boston: Brooks/Cole, CENGAGE Learning.

Huynh, Thomas V., and John S. Omundson. 2007. “An Integrated Systems Engineering Methodology for Analyzing Systems of Systems Architectures.” Paper presented at the Asia-Pacific Systems Engineering Conference, Singapore, March 23.

Imagine That Inc. ExtendSim Overview. 2016. Accessed April 21. http://www.extendsim.com/prods_overview.html.

Janes. 2016. “CDL Hawklink AN/ARQ-59 Radio Terminal Set.” Accessed April 24. https://janes.ihs.com/Janes/Display/1523829.

Johns Hopkins APL. 1995. “The Cooperative Engagement Capability.” Johns Hopkins APL Technical Digest 16: 377–396.

Keck, Zachary. 2014. “China’s “Nine-Dash Line” is Dangerous.” *The Diplomat*. February 19. http://thediplomat.com/2014/02/chinas-nine-dash-line-is-dangerous/.

Klamp, John. 2015. “Tactical Undersea Network Architectures (TUNA).” Accessed April 26. http://www.darpa.mil/program/tactical-undersea-network-architectures.

Kline, Jeffrey E. 2015. “Maritime War of 2030.” Presented at the Warfare Innovation Workshop, Monterey, California, September 21–24.

———. 2016. “A Tactical Doctrine for Distributed Lethality.” Center for International Maritime Security. Accessed April 15, 2015. http://cimsec.org/tactical-doctrine-distributed-lethality/22286.

LaGrone, Sam. 2015. “Mabus: F-35 Will Be ‘Last Manned Strike Fighter’ the Navy, Marines ‘Will Ever Buy or Fly’” USNI News, April 15. https://news.usni.org/2015/04/15/mabus-f-35c-will-be-last-manned-strike-fighter-the-navy-marines-will-ever-buy-or-fly.

Lapic, Stephan, Chris Meagher, Daryl Ching, Lester Chong, Isabelle Labbé, Sarah Dumoulin, Martin Jordan, and Rob Thompson. 2013. “Maritime Operations in Disconnected, Intermittent, and Low-Bandwidth Environments.” Paper presented at the 18th International Command and Control Research and Technology Symposium, Alexandria, Virginia, June 19–21.

Liquid Robotics, Inc. 2016. “Reimagine Ocean Monitoring and Operations. Unmanned Robots Powered by Nature.” Accessed April 26. http://www.liquid-robotics.com/platform/overview/.

Lockheed Martin Corporation. 2001. “MH-60R: 21st Century Multi-Mission Maritime Excellence.” Trifold Brochure Advertisement.

———. 2016. MH-60R Seahawk. Accessed April 21. http://www.lockheedmartin.com/us/products/mh60r.html.

Maier, Mark W., and Eberhardt Rechtin. 2009. *The Art of Systems Architecting,* 3rd ed. Boca Raton: CRC Press.

McConnell, Jeffrey H. 2013. "Naval Integrated Fire Control-Counter Air Capability-Based System of Systems Engineering." Dahlgren, Virginia: Naval Surface Warfare Center, Dahlgren Division.

McDowell, Robin. 2011, July 21. "A look at the top issues at Asian security meeting." Yahoo! News. https://www.yahoo.com/news/look-top-issues-asian-security-meeting-095756273.html?ref=gs.

Misra, Sudip and Subhas Chandra Misra and Isaac Woungang, editors. 2009. Guide to Wireless Mesh Networks. Swindon: Springer-Verlag London Limited.

Moore, Craig R., Mark H. Luesse, and Kenneth W. O'Haver. 2002. "A Low-Cost Cooperative Engagement Capability Array Antenna." *Johns Hopkins APL Technical Digest* 23: 172–86.

Naval Doctrine Publication (NDP) 1. 2010. "Naval Warfare." Washington, D.C.: OPNAV.

Naval Expeditionary Combat Command (NECC). 2012. "Adaptive Force Package Concept of Operations (CONOPS)." Virginia Beach, Virginia: NECC.

Naval Postgraduate School. 2015. "Program Overview: What is Systems Engineering Analysis." Accessed April 2016. https://my.nps.edu/web/sea/overview.

Northrup Grumman. 2015. "MQ-8B Fire Scout." Accessed April 24. http://www.northropgrumman.com/Capabilities/FireScout/Documents/pageDocuments/MQ-8B_Fire_Scout_Data_Sheet.pdf.

Office of the Chief of Naval Operations (OPNAV). 2007. "Universal Naval Task List (UNTL) Version 3.0 OPNAVINST 3500.38B/MCO3500.26A/USCG COMDINST 3500.1B." Washington, D.C.: OPNAV.

Office of the Secretary of Defense (OSD). 2005. Unmanned Aircraft Systems Roadmap 2005–2030. Arlington County: Department of Defense.

Petty, Nicola Ward, and Shane Dye. "Triangular Distributions." Statistics Learning Centre. June 11, 2013. Accessed April 25. https://learnandteachstatistics.files.wordpress.com/2013/07/notes-on-triangle-distributions.pdf.

Pisacane, Vincent L. 2005. "EA465: Lectures in Spacecraft Communications and Power." Annapolis: United States Naval Academy.

Ragsdale, Cliff T. *Spreadsheet Modeling and Decision Analysis,* 6th ed. Boston: CENGAGE Learning.

Reynolds, Kevin. 2015. "Additive Manufacturing." Presentation at the Warfare Innovation Workshop, Monterey, California, September 21–24.

Rowden, Thomas, Peter Gumataotao, and Peter Fanta. 2015. "Distributed Lethality." *Proceedings*. http://www.usni.org/magazines/proceedings/2015-01/distributed-lethality.

SPEC Innovations. 2016. "Innoslate." https://www.innoslate.com/.

Tangredi, Sam. 2013. *Anti-Access Warfare: Countering A2/AD Strategies*. Annapolis: Naval Institute Press.

Under Secretary of Defense (Acquisition, Technology, and Logistics) (USD (ATL)). 2005. DOD Guide for Achieving Reliability, Availability, and Maintainability. Washington, D.C.: Department of Defense.

ViaSat. 2015a. "MIDS-LVT(1): Link 16 Terminal." Accessed April 24. https://www.viasat.com/sites/default/files/media/documents/mids_lvt-1_datasheet_039_web.pdf.

———. 2015b. "Move Out/Jump Off Kit." Accessed April 24. https://www.viasat.com/sites/default/files/media/documents/mojo_datasheet_008_web.pdf.

Vitech. 2016. "CORE 9: Product Design and Development Success Through Integrated Systems Engineering." Accessed April 18. http://www.vitechcorp.com/products/core.shtml.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California